PB190264

CONTROL TECHNIQUES FOR CARBON MONOXIDE, NITROGEN OXIDE, AND HYDROCARBON EMISSIONS FROM MOBILE SOURCES

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U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Environmental Health Service

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CONTROL TECHNIQUES
FOR
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FROM
MOBILE SOURCES

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Environmental Health Service
National Air Pollution Control Administration
Washington, D. C.
March 1970

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402 - Price $1.25

National Air Pollution Control Administration Publication No. AP-66

PREFACE

Throughout the development of Federal air pollution legislation, the Congress has consistently found that the States and local governments have the primary responsibility for preventing and controlling air pollution at its source. Further, the Congress has consistently declared that it is the responsibility of the Federal government to provide technical and financial assistance to State and local governments so that they can undertake these responsibilities.

These principles were reiterated in the 1967 amendments to the Clean Air Act. A key element of that Act directs the Secretary of Health, Education, and Welfare to collect and make available information on all aspects of air pollution and its control. Under the Act, the issuance of control techniques information is a vital step in a program designed to assist the States in taking responsible technological, social, and political action to protect the public from the adverse effects of air pollution.

Briefly, the Act calls for the Secretary of Health, Education, and Welfare to define the broad atmospheric areas of the Nation in which climate, meteorology, and topography, all of which influence the capacity of air to dilute and disperse pollution, are generally homogeneous.

Further, the Act requires the Secretary to define those geographical regions in the country where air pollution is a problem—whether interstate or intrastate. These air quality control regions are designated on the basis of meteorological, social, and political factors which suggest that a group of communities should be treated as a unit for setting limitations on concentrations of atmospheric pollutants. Concurrently, the Secretary is required to issue air quality criteria for those pollutants he believes may be harmful to health or welfare, and to publish related information on the techniques which can be employed to control the sources of those pollutants.

Once these steps have been taken for any region, and for any pollutant or combination of pollutants, then the State or States responsible for the designated region are on notice to develop ambient air quality standards applicable to the region for the pollutants involved, and to develop plans of action for meeting the standards.

The Department of Health, Education, and Welfare will review, evaluate, and approve these standards and plans and, once they are approved, the States will be expected to take action to control pollution sources in the manner outlined in their plans.

At the direction of the Secretary, the National Air Pollution Control Administration has established appropriate programs to carry out the several Federal responsibilities specified in the legislation.

Control Techniques for Carbon Monoxide, Nitrogen Oxide, and Hydrocarbon Emissions from Mobile Sources is one of a series of documents to be produced under the program established to carry out the responsibility for developing and distributing control technology information. Previously, on February 11, 1969, control technique information was published for sulfur oxides and particulate matter.

In accordance with the Clean Air Act, a National Air Pollution Control Techniques Advisory Committee was established, having a membership broadly representative of industry, universities, and all levels of government. The committee, whose members are listed following this discussion, provided invaluable advice in identifying the best possible methods for controlling the pollution sources, assisted in determining the costs involved, and gave major assistance in drafting this document.

As further required by the Act, appropriate Federal departments and agencies, also listed on the following pages, were consulted prior to issuance of this document. A Federal consultation committee, comprising members designated by the heads of 17 departments and agencies, reviewed the document, and met with staff personnel of the National Air Pollution Control Administration to discuss its contents.

During 1967, at the initiation of the Secretary of Health, Education, and Welfare, several government-industry task groups were formed to explore mutual problems relating to air pollution control. One of these, a task group on control technology research and development, looked into ways that industry representatives could participate in the review of the control techniques reports. Accordingly, several industrial representatives, listed on the following pages, reviewed this document and provided helpful comments and suggestions. In addition, certain consultants to the National Air Pollution Control Administration also revised and assisted in preparing portions of this document. These also are listed on the following pages.

The Administration is pleased to acknowledge efforts of each of the persons specifically named, as well as those of the many not so listed who contributed to the publication of this volume. In the last analysis, however, the National Air Pollution Control Administration is responsible for its content.

The control of air pollutant emissions is a complex problem because of the variety of sources and source characteristics. Technical factors frequently make necessary the use of different control procedures for different types of sources. Many techniques are still in the development stage, and prudent control strategy may call for the use of interim methods until these techniques are perfected. Thus, we can expect that we will continue to improve, refine, and periodically revise the control techniques information so that it will continue to reflect the most up-to-date knowledge available.

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SUMMARY

This document considers the techniques for the control and prevention of the emission of carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC) from all types of vehicles. This approach has been pursued because measures taken to reduce emissions of one contaminant may affect emissions of another. Although these mobile sources emit other contaminants, the discussion in this document is restricted to those cited above.

Transportation in general is a major source of CO, NO_x, and HC. In 1968 estimated emissions from vehicles in the United States were 64 million tons of CO, 8 million tons of NO_x, and 17 million tons of hydrocarbons. The primary mobile source of these emissions is the gasoline-powered motor vehicle. Other significant sources are diesel-powered vehicles and aircraft. Lesser sources are vessels and boats operating on inland waterways, off-road utility and recreational vehicles, construction equipment, motorcycles, power lawn mowers, and other utility tools.

Emissions from a gasoline-powered vehicle without any emission control systems originate from the fuel tank, carburetor, crankcase, and engine exhaust. The exhaust is the source of almost all CO and NO_x and more than half of the HC. Formation of the three in the combustion chamber is influenced by such factors as air-fuel ratio, ignition timing and quality, intake-manifold vacuum, engine compression ratio, engine speed and load, fuel distribution between cylinders and within a cylinder, coolant temperature, and combustion chamber configuration and deposits. Emission constituents can react chemically after release into the atmosphere. Several reactivity indexes have been proposed and are used to evaluate and quantify the tendency of certain HC to react photochemically.

LEGISLATIVE PROGRESS

The Clean Air Act, as amended, is the legislative basis for the Federal air pollution control program for new motor vehicles; however, California pioneered with legislation in this area in 1947. Initial legislation by the Federal Government was in 1955 with the enactment of the Air Pollution Control Act. Subsequent legislation resulted in mandatory installation of crankcase controls on all new cars sold in California beginning in 1963, and on new cars sold nationwide beginning with the 1968 models. The automobile manufacturers, however, had voluntarily installed these devices on all new cars sold in California beginning with the 1961 models and on new cars sold nationwide beginning with the 1963 models. Exhaust emission standards for HC and CO, applicable to new cars sold in California, became effective with the 1966 model year. Federal regulations prescribed the same standards for new light-duty vehicles sold nationally beginning with the 1968 models, and more stringent standards beginning with the 1970 models. Federal regulations also prescribe standards for evaporative HC emissions beginning with the 1971 models.

Federal standards for new vehicles will cause a decrease in HC and CO emissions beyond 1980 in spite of the increase in vehicle population. Nitrogen oxide emissions, however, will continue to increase at a rate augmented by efforts to control CO and HC emissions, unless NO_x emissions are specifically controlled. Prior to 1970, exhaust emission regulations for light-duty vehicles were expressed in terms of concentrations, but beginning with the 1970 standards, mass units, considered to be more equitable for various vehicle sizes, are being used.

Although the Federal Government has specifically preempted the authority to set emission standards for new vehicles, a special waiver provision permits the State of California to establish and enforce more restrictive standards and procedures than the national standards. California has already established standards for NO_x beginning with 1971 models, becoming more stringent in 1972, and still more stringent in 1974. The California standards for HC in 1972 are also more strict than existing Federal standards. State standards for evaporative emissions became effective in California beginning with 1970 models.

Automobile manufacturers may request that prototype new vehicles be certified as complying with established emission standards, before production vehicles of substantially the same construction are sold. The National Air Pollution Control Administration (NAPCA) maintains its principal laboratory for this purpose in Ypsilanti, Michigan, where prototype new vehicles can be certified and vehicles in public use are checked to determine the durability or continued effectiveness of control devices and systems in service. A surveillance program conducted by the State of California indicates that the effectiveness of control systems for HC and CO decreases in service, but that they are becoming generally more effective with succeeding years (although not significantly for HC in 1968 and 1969) even though applicable CO and HC emission standards have not changed for the vehicles surveyed.

STATE EMISSION CONTROL PROGRAMS

Federal authority for the control of vehicular emissions ends with the sale of new vehicles. States should be encouraged to take action to ensure the continued operation and efficiency of emission control systems and other automotive systems that affect emissions. Reduced effectiveness of control systems after they leave the manufacturer may be due to a number of causes, including gross malfunction, improper adjustment, and deliberate removal or inactivation.

A state may determine that its air quality in certain areas is such that a state control program for vehicle emissions is necessary to augment the degree of control provided by the Federal standards for new cars sold since 1968. Options available to the states, such as inspection and maintenance programs may reduce CO and HC exhaust emissions.

Other methods are available to check crankcase control devices and may be considered in addition to exhaust inspection. Future vehicles will be equipped with evaporative control systems. Inspection and maintenance of these may be desirable, but little information on possible programs is currently available.

States should select methods for reducing vehicular emissions for both the control of existing air pollution and the prevention of future air pollution. Many practical difficulties may arise in implementing a statewide inspection and a maintenance system, but experience now being obtained by several states should be of assistance.

Five programs of the Coordinating Research Council, which are concerned with surveillance, maintenance, and inspection, are of particular significance to this document, even though the bulk of information generated by them will not be available until 1971 or 1972. These are Cooperative Air Pollution Engineering (CAPE) Projects 14 through 18.

Although it has been shown that various inspection and maintenance programs can reduce emissions of CO and HC, additional data are needed to demonstrate the cost and cost-effectiveness of such programs in practice.

In addition to inspection and maintenance of vehicles, other actions that may assist in reducing emissions from motor vehicles include the following:

1. Substitution of public transportation, in part, for the private automobile in urban areas.
2. Application of exhaust emission control devices (which, reportedly, will

be available soon) to pre-1968 (pre-exhaust-controlled) light-duty vehicles.

3. Planning of freeways and traffic control systems to minimize stop-and go-driving and thus affect emissions.

States may wish to consider long-range planning with respect to vehicle emissions. Some options of this type are listed below:

1. Planning for emergency actions to reduce vehicular emissions during periods when unfavorable weather conditions create an air pollution emergency.
2. Planning for governmental certification of maintenance and inspection personnel to protect the public from mechanics who inadvertently cause an increase in vehicular emissions through maladjustment or improper maintenance of engine components.

As an aid in estimating the quantity of vehicle emissions in a certain region, a procedure developed by the National Air Pollution Control Administration is available for use by states or communities. It requires only information concerning vehicle registrations or vehicle miles to arrive at estimated emissions.

EMISSION CONTROL SYSTEMS

Emission control systems in use on current-model motor vehicles include positive crankcase ventilation systems (in which vapors are routed to the fuel induction system) and exhaust emission control systems (and evaporative controls in California beginning with 1970 models). The exhaust controls are of two general types and reduce emissions either by oxidizing CO and unburned HC in the exhaust system or by minimizing their quantities emanating from the engine cylinders. The air injection system was used on some 1968 and 1969 domestic models and consists of employment of an air pump to inject air into the exhaust manifold at each exhaust valve. The second commonly used approach for controlling exhaust CO and HC is currently more prevalent and consists of engine modifications to minimize formation of contaminants in the cylinders. This approach consists of designing engines with improved air-fuel mixing and distribution systems and tailoring ignition characteristics for optimum emission control.

Evaporative controls, required on new cars in California beginning with 1970 models and nationally in 1971, collect vapors from the fuel tank and carburetor and vent them either to the crankcase or to an activated-carbon canister. In either case, the collected vapors are eventually returned to the fuel induction system and burned in the engine.

Control systems for NO_x emissions are under development. Some of the technical approaches being considered are exhaust gas recirculation and catalytic reduction. Since systems incorporating these approaches have not been produced in large numbers, accurate data on costs are not available.

FUEL MODIFICATION

It is sometimes possible to alter emissions of CO, NO_x, and HC by modifying the volatility of the fuel, its constituent hydrocarbon types, or its additive content.

The use of liquefied petroleum gas (LPG), liquefied natural gas (LNG), and compressed natural gas (CNG) as fuels for conventional vehicle engines is being considered and appears promising. Use of these fuels, however, involves problems of fuel distribution and fuel storage and fairly high installation and engine modification costs. Supplies of these fuels are also very limited compared to currently used vehicle fuels.

State governments may wish to encourage use of specific mobile power sources known for their low emissions. These include the automotive gas turbine, the steam engine, electric drives, the free-piston engine, the Stirling engine, and the stratified-charge engine.

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CONTROL TECHNIQUES FOR CARBON MONOXIDE, NITROGEN OXIDE, AND HYDROCARBON EMISSIONS FROM MOBILE SOURCES

1. INTRODUCTION

Pursuant to authority delegated to the Commissioner of the National Air Pollution Control Administration, *Control Techniques for Carbon Monoxide, Nitrogen Oxide, and Hydrocarbon Emissions from Mobile Sources* is issued in accordance with Section 107(c) of the Clean Air Act as amended (42 U.S.C. 1857-18571).

The predominant source of carbon monoxide (CO), nitrogen oxide (NO_x), and hydrocarbon (HC) from mobile combustion sources is the exhaust gas from gasoline-fueled engines. An example of the difficulties involved in eliminating exhaust emissions is portrayed in Figure 1-1. This graph illustrates, for a typical range, that exhaust CO and HC emissions could be reduced by increasing the ratio of air to fuel to the point where more air is present than is required for complete combustion of the fuel to carbon dioxide and water (i.e., an air-fuel ratio greater than the stoichiometric ratio). Maximum emissions of NO_x, however, would occur under such conditions. At very low air-fuel ratios, the NO_x emissions could be reduced, but high concentrations of CO and HC would be produced. At the extremely high air-fuel ratios where all three emissions could, theoretically, be low, operating difficulties such as misfire and stalling would be encountered with most commercially available, gasoline-fueled, internal combustion engines, causing poor performance and high emissions of CO and HC.

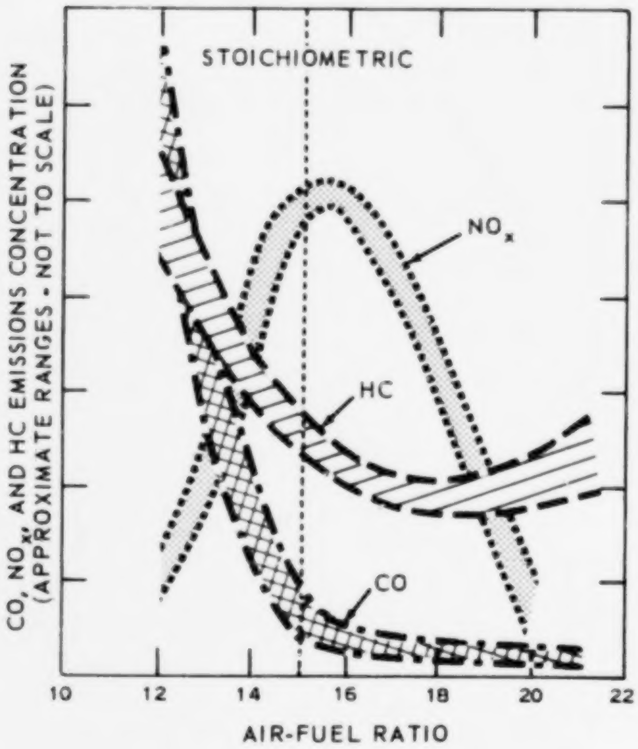

Figure 1-1. Effects of air-fuel ratio on exhaust composition.[1]

Various approaches and devices have been developed, and others are under development for controlling emissions of CO, NO_x, and HC from mobile sources. These encompass various principles of operation, degrees of effectiveness, complexity, and cost. It is the purpose of this document to present a review of these control methods and to summarize Federal and state emission control programs as they relate to emissions of CO, NO_x, and HC from mobile sources.

The principal mobile sources that generate CO, NO_x, and HC emissions are described individually. Various techniques to control such emissions from these sources are reviewed. Technical considerations of the more prominent and feasible design modifications, alternative power sources, fuel modifications, auxiliary devices, and alternative transportation modes are presented. Sections on source evaluation, equipment costs, cost effectiveness analysis, and current research and development also are included. Pertinent references are presented at the end of each section.

While some data are presented herein on quantities of CO, NO_x, and HC emitted to the atmosphere from mobile sources, the subject of the effects of these substances on health and welfare is considered in the companion documents listed below:

1. AP-62, *Air Quality Criteria for Carbon Monoxide*
2. AP-63, *Air Quality Criteria for Photochemical Oxidants*
3. AP-64, *Air Quality Criteria for Hydrocarbons*
4. *Air Quality Criteria for Nitrogen Oxides**

1. REFERENCE FOR SECTION 1

1. Trayser, D. A. et al. A Study of the Influence of Fuel Atomization, Vaporization, and Mixing Processes on Pollutant Emissions from Motor-Vehicle Power Plants. Battelle Memorial Institute. Columbus, Ohio. April 30, 1969. p. 16.

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*To be issued at a later date.

2. BACKGROUND INFORMATION

2.1 DEFINITIONS

The following definitions apply to terms used in this document:

1. "Air carrier fleet" includes all civilian aircraft transporting persons or property for hire.
2. "Bottom dead center" or "bottom center" refers to the position of a piston in an internal combustion engine when it has reached the bottom (or end) of its travel in the cylinder during the intake or power strokes.
3. "Blowby" means the leakage of the air-fuel charge or the combustion gases past the piston rings and into the crankcase during the compression or power strokes in an internal combustion engine.
4. "Closed-cycle engines" are engines in which the working fluid is not exhausted to the atmosphere but is used over and over again.
5. "Combustion chamber" means a volume inside an internal combustion engine bounded by the cylinder head, the top surface of the piston, and the cylinder wall. Within this volume, the air-fuel mixture is ignited and burns.
6. "Condenser" is the device in which vapor is cooled sufficiently to cause it to change to a liquid phase.
7. "Day" means one 24-hour period of time.
8. "Diesel Engine" is a compression-ignition, internal-combustion engine, which operates on the limited-pressure thermodynamic cycle and generally uses a hydrocarbon fuel.
9. "Diurnal breathing losses" means fuel evaporative emissions as a result of the fluctuations in temperature to which the fuel system is exposed during one day.
10. "Exhaust emission" means substances emitted to the atmosphere from any opening downstream from the exhaust port of a motor vehicle engine.
11. "External-combustion engine" is an engine in which the working fluid (such as steam) is separated from the products of combustion by a wall or barrier through which heat must pass.
12. "Fuel evaporative emissions" means vaporized fuel emitted into the atmosphere from the fuel system of a motor vehicle.
13. "Fuel percolation" refers to the movement of fuel from the passages in the carburetor to the carburetor bore and into the intake manifold as a result of fuel vaporization, especially during the hot soak period.
14. "Fuel system" means the combination of fuel tank, fuel pump, fuel lines, and carburetor or fuel injection components, and includes all vents and fuel evaporative emission control systems or devices.
15. "General aviation fleet" is a broad category consisting of all civilian aircraft except those of the air carrier fleet.
16. "Heavy-duty vehicle" means a motor vehicle weighing more than 6,000 pounds gross vehicle weight.

17. "Hot soak" means the transfer of heat from hot components of an engine to cooler components such as the carburetor. The "hot soak" period begins immediately after the engine is stopped.
18. "Inspection" is meant to cover a visual check for the presence of emission control devices or measurement of emissions on vehicles, and implies that adjustment, maintenance, certification, or some other subsequent action will be taken if the inspection shows it to be necessary or appropriate.
19. "Internal-combustion engine" is an engine in which the products of combustion are the working fluid and come into direct contact with the expander (piston or turbine blade).
20. "Lean air-fuel ratio" describes a mixture of air and fuel in which the ratio of mass of air to mass of fuel is high compared to a stocihiometric mixture. This term often causes confusion because a *high* A/F (air to fuel) ratio indicates a *lean* mixture.
21. "Lean surge" refers to the tendency for the power output of an engine to pulsate or surge because of a lean air-fuel ratio.
22. "Light-duty vehicle" means a motor vehicle designed for transportation of persons or property on a street or highway and weighing 6,000 pounds gross vehicle weight or less.
23. "light ends" refers to the more volatile portion of a petroleum fraction, the material that evaporates first.
24. "Maximum rated horsepower" means the maximum brake horsepower output of an engine as stated by the manufacturer in his sales and service literature.
25. "Misfire" means that the air-fuel charge in a cylinder did not ignite and, therefore, did not supply any power during the cycle in which the misfire occurred.
26. "Open-cycle engines" are engines in which the working medium or fluid is exhausted to the atmosphere, such as in noncondensing steam engines and internal-combustion engines.
27. "Reactivity" is a measure of the tendency of certain substances to enter into atmospheric reactions in the presence of nitrogen oxides and ultraviolet radiation (sunlight).
28. "Recuperator and Regenerator" are heat exchangers. They may be used to preheat combustion air or to heat or cool working fluids.
29. "Reid vapor pressure" (RVP) is a composite, empirical value which reflects the cumulative effect of the individual vapor pressures of the different motor fuel fractions. It provides both a measure of how readily a fuel can be vaporized to provide a combustible mixture at low temperatures, and an indicator of the tendency of the fuel to vaporize and cause vapor lock at high temperatures. Determinations of RVP are made at 100°F with a vapor to liquid volume ratio of 4 to 1.
30. "Rich air-fuel ratio" describes a mixture of air and fuel in which the ratio of mass of air to mass of fuel is lower than would be required to burn the fuel completely (i.e., lower than that of a stoichiometric mixture). This term often causes confusion because a *low* A/F (air to fuel) ratio indicates a *rich* mixture.
31. "Spark-ignition engine" is an internal-combustion engine, which operates on the Otto thermodynamic cycle, in which gasoline fuel is generally used, the fuel-air mixture being ignited by an electric arc.
32. "Specific fuel consumption" is a measure of engine fuel consumption per unit time at a specified power level. The units of this expression

generally used in United States engineering practice are pounds of fuel per horsepower-hour (lb fuel/hp-hr).

33. "Stalling" refers to the loss of power from an engine, either momentarily or completely, because of some malfunction or misuse.
34. "Stoichiometric mixture" is a term used to define an air-fuel mixture which is theoretically of the correct ratio to obtain complete combustion without excess oxygen.
35. "Surveillance" is meant to include measurement of emissions, on vehicles which supposedly represent the entire population of vehicles in an area, possibly on a random spot-check basis. It is usually used to evaluate emissions in the area and/or performance characteristics of vehicles.
36. "System or device" includes any motor vehicle equipment or engine modification which controls or causes the reduction of substances emitted from motor vehicles or motor vehicle engines to the atmosphere.
37. "Top dead center" or "top center" refers to the position of a piston in an internal combustion engine when it has reached the top (or end) of its travel in the cylinder during the compression or exhaust strokes.
38. "Working fluid" is the fluid that is heated either directly or indirectly and which produces work in the engine expander.

2.2 TYPES AND NUMBERS OF MOBILE SOURCES

Gasoline-powered motor vehicles constitute the major mobile sources of CO, NO_x, and HC emissions in the United States. To a far lesser extent, diesel-powered motor vehicles, aircraft, railroad locomotives, vessels and boats operating on inland waterways, off-road utility and recreational vehicles, heavy construction equipment, motorcycles, power lawnmowers, and similar utility tools also contribute. Populations of various vehicles as of the latest date for which information is available are contained in Tables 2-1 and 2-2. The relative contributions of mobile sources by major categories are included in a table at the end of Section 2.

Emission characteristics of the gasoline-powered, light-duty motor vehicle have been the subject of intensive study with respect to both the nature and extent of emissions, and numbers of vehicles and emission characteristics are well documented. Methods of controlling emissions from diesel-powered motor vehicles have been studied, with particular emphasis on smoke and odorous emissions. Populations of diesels are fairly well documented, and standards for CO, NO_x, and hydrocarbon emissions are to be proposed in California in 1971.

Little has been done toward determining emission characteristics of locomotive diesel engines. Numbers of units in service and total locomotive miles are available from the U. S. Interstate Commerce Commission.

Characteristics of emissions from outboard engines are not well documented. Essentially all, however, are two-stroke-cycle engines, indicating high hydrocarbon concentrations in the exhaust relative to four-stroke-cycle engines. Most are run at high power levels resulting in large exhaust flow rates, since power output is increased as mass flow rate through the engine increases. Complete data on larger commercial vessels that operate on inland waterways as to types of power-plants are not available.

Off-road utility vehicles such as four-wheel-drive, dune buggies, etc., are comparatively few in number and usually powered by conventional gasoline engines. Heavy construction equipment is powered principally by diesel engines, but a count of equipment actually in use is not obtainable. Motorcycle engines are now predominantly two-stroke-cycle and, reportedly, are high hydrocarbon emitters in terms of concentrations and flow rates for the same reasons that outboard motors are believed to be. Although the frontal area of a motorcycle with a rider is

Table 2–1. POPULATION OF MOBILE SOURCES OF EMISSIONS IN USE IN THE UNITED STATES

(as of 1968, except as noted)

Vehicle	Power plant	Number in use	Reference
Passenger cars	Gasoline	83,698,100	1
Trucks (total)	Gasoline and diesel	16,998,546	1
Trucks	Diesel	416,454 (1967)	2
Buses (total)	Gasoline and diesel	351,804	1
Buses	Diesel	65,742 (1967)	2
Motorcycles	Gasoline	1,753,000 (1966)	3
Off-highway wheel type tractors (contractors)	Gasoline and diesel	21,647[a]	4
Wheel type tractors (except contractors)	Gasoline and diesel	2,128,914[a]	4
Tracklaying tractors	Gasoline and diesel	245,595[a]	4
Aircraft (non-military)	Gas turbine	2,577 (1967)	5
Aircraft (non-military)	Piston engine	151,111 (1967)	5
Aircraft (military)	Predominantly gas turbine	33,749 (1967)	5
Locomotives	Diesel	27,045	6
Ships	Diesel	Not available	
Outboard motors	Gasoline	6,988,000	7
Boats (registered, pleasure)	Outboard	3,965,502	8
Boats (registered, pleasure)	Inboard	543,216	8
Utility tools	Gasoline	Not available	

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[a] Total units manufactured 1959 through first 9 months of 1968 are given.

not large compared to that of an automobile, the drag coefficient involved is greater than that for a streamlined vehicle. Thus, fairly high power levels and associated high mass flow rates through the engine are required to maintain high speeds.

2.2.1 Growth History and Projections

Because of their relative importance in the United States, numbers of motor vehicles and aircraft in use are well documented. The numbers of the majority of other mobile sources are not. Table 2-2 presents data for 1968 populations of passenger cars, trucks, and buses for each of the 50 states. Projections of vehicle miles are also studied extensively, and totals for the period from 1960 to 1990 are indicated in Figure 2-1. The total miles for diesel vehicles are assumed to be 12.1 percent of the total truck and bus miles. (Total miles minus passenger car miles times 12.1 percent equals diesel miles.)

Example, for 1975:

$$(1210 \times 10^9 - 990 \times 10^9)\ 12.1\%$$

$$= 27 \times 10^9 \text{ diesel miles}$$

Numbers of vehicles and vehicle miles are related in that the average passenger car can be considered to be driven 9,400 miles per year. Therefore, dividing total passenger car miles by 9,400 gives an indication of the number of cars registered in that year.

Numbers of aircraft in the U.S. air carrier fleet, by type of power source, for 1960 to 1967, and estimated for 1968 to 1979, are indicated graphically in Figure 2-2, and similarly for the U.S. general aviation fleet in Figure 2-3.

Table 2-2. 1968 U.S. MOTOR VEHICLE REGISTRATIONS, BY STATES AS OF THE END OF THE REGISTRATION YEAR[5]

As of the End of the Registration Year

These data do not include publicly-owned vehicles with the exception of school buses. Publicly-owned vehicles are estimated to be approximately 1.4 million in 1969.

STATE	Passenger Cars[1]	Trucks	Buses[2]	Total Motor Vehicles	Taxicabs[3]	Motor-cycles	Trailers and Semi-trailers: Tourist[4]	Commercial	Total
Alabama	1,397,860	318,404	2,235	1,718,499	2,266	25,745	21,350	43,683	65,033
Alaska	80,671	31,819	442	112,932	278	5,702	11,814	2,277	14,091
Arizona	717,376	204,627	2,035	924,038	221	25,220	67,177	66,651	133,828
Arkansas	699,877	300,060	4,160	1,004,097	624	16,025	......	......	85,132
California	9,245,913	1,515,613	(1)	10,761,526	4,954	362,715	......	......	1,099,330
Colorado	967,724	286,407	(5)	1,274,131	(5)	28,594	49,420	77,898	127,318
Connecticut	1,322,852	132,238	5,953	1,461,043	650	23,424	63,161	15,471	78,632
Delaware	237,177	42,491	(6)	279,668	(5)	3,631	......	......	20,334
Dist. of Col.	225,863	16,615	4,054	246,532	10,150	2,613	......	1,685	1,685
Florida	3,249,080	435,062	9,873	3,693,015	104,642	72,895	150,267	306,095	456,362
Georgia	1,895,924	397,000	2,315	2,295,239	(5)	29,000	95,000	31,000	126,000
Hawaii	309,730	35,095	(5)	344,825	......	9,632	8,655	890	9,545
Idaho	409,876	70,058	1,557	481,491	491	22,537	60,230	40,717	100,947
Illinois	4,345,857	581,130	14,717	4,941,704	7,442	89,131	96,101	241,670	337,771
Indiana	2,190,091	487,835	10,612	2,688,538	(5)	69,031	144,115	53,576	197,691
Iowa	1,328,976	329,039	......	1,658,015	......	41,824	29,836	140,993	170,829
Kansas	1,060,500	455,000	(6)	1,515,500	(5)	35,000	19,000	110,000	129,000
Kentucky	1,333,300	341,100	6,603	1,681,003	1,750	28,200	19,400	16,800	36,200
Louisiana	1,311,154	336,610	6,191	1,653,955	(5)	24,977	92,400	44,560	136,960
Maine	375,955	95,965	240	472,160	675	6,345	......	......	131,475
Maryland	1,453,991	203,545	6,411	1,663,950	(5)	22,119	......	......	74,457
Massachusetts	2,082,000	209,000	7,550	2,298,550	(5)	32,000	......	......	158,000
Michigan	3,841,135	577,156	......	4,418,291	......	120,084	77,895	480,235	558,130
Minnesota	1,672,214	379,846	6,354	2,058,414	(5)	60,516	255,825	66,276	322,101
Mississippi	831,662	267,536	9,176	1,108,374	1,545	11,279	28,450	14,099	42,549
Missouri	1,798,000	490,700	3,780	2,292,480	(5)	39,250	......	......	175,700
Montana	311,893	154,739	......	466,632	......	17,175	......	......	48,185
Nebraska	791,794	250,829	4,393	1,047,016	300	21,603	91,996	844	92,840
Nevada	225,000	66,000	(5)	291,000	(5)	13,000	8,800	21,000	29,800
New Hampshire	272,000	41,000	(6)	313,000	(6)	7,000	......	......	35,000
New Jersey	2,956,630	307,932	5,425	3,269,987	4,623	38,502	64,453	53,935	118,388
New Mexico	411,218	156,344	2,094	569,656	169	14,939	24,208	26,592	50,800
New York	5,571,921	597,900	13,900	6,183,721	68,300	71,700	......	......	314,400
North Carolina	2,021,021	476,145	20,000	2,517,166	3,363	32,448	......	......	224,697
North Dakota	260,288	140,678	37	401,003	......	9,358	7,755	1,127	8,882
Ohio	4,714,450	538,978	7,891	5,261,319	(5)	121,248	98,749	274,011	372,760
Oklahoma	1,173,955	433,996	684	1,608,635	1,357	34,598	37,352	27,028	64,380
Oregon	1,088,797	76,769	1,808	1,167,374	(5)	31,981	95,147	21,192	116,339
Pennsylvania	4,828,372	663,113	22,047	5,513,532	......	113,612	47,922	107,764	155,686
Rhode Island	397,448	47,347	425	445,220	320	6,455	......	......	27,076
South Carolina	976,065	209,119	7,424	1,192,608	1,610	12,143	11,862	16,621	28,483
South Dakota	283,678	122,943	884	407,505	(5)	9,663	......	......	43,785
Tennessee	1,748,111	351,223	2,717	2,102,051	2,450	32,848	2,010	23,555	25,565
Texas	4,752,000	1,306,425	20,717	6,079,142	......	96,000	55,000	500,000	555,000
Utah	498,608	169,628	228	668,464	(4)	16,575	......	......	33,963
Vermont	170,408	27,602	96	198,106	......	5,263	......	......	22,271
Virginia	1,718,114	300,816	4,877	2,023,807	10,797	25,517	52,727	60,225	112,952
Washington	1,479,775	419,600	4,600	1,903,975	1,225	50,950	127,250	112,825	240,075
West Virginia	610,649	153,700	4,800	769,149	649	18,000	27,000	14,000	41,000
Wisconsin	1,731,037	299,523	11,351	2,041,911	(5)	76,209	20,470	36,815	57,285
Wyoming	146,103	73,746	780	220,629	(5)	6,820	14,398	32,312	46,710
Totals	83,543,093	15,926,049	241,436	99,710,578	230,851	2,091,096	2,077,195	3,084,420	7,683,003

[1]—Includes taxicabs. [2]—Includes school buses whether fee or non fee. [3]—Included with passenger cars, but shown separately for your convenience. [4]—Includes house or camp trailer and light 2-wheel trailers pulled by car or utility truck. [5]—Included with passenger cars. [6]—Included with trucks.

NOTE: In the above tabulation we (Automotive Industries Magazine) have endeavored to make as accurate a count as existing conditions permit. This census is compiled from material secured direct from the state motor vehicle commissioners. Wherever possible duplications occasioned by transfers and non-resident registrations have been eliminated. Data are for the registration year, even though this necessitates partial estimates. In the case of those states whose registration year ends February or March of the following year, or whose data are not compiled by the time we go to press. (Courtesy of Automotive Industries Magazine.)

2.2.2 Power Plants

The most common power plant in this country for mobile use is the four-stroke-cycle spark-ignited internal-combustion engine. It is used to a large extent in ground vehicles. Its largest application is in passenger cars and light-duty trucks. Figure 2-4 shows trends in United States passenger car engine design. The next most common power plant is the four- and two-stroke-cycle, compression-ignition, internal-combustion engine, which is frequently referred to as the diesel. It is used to propel large trucks, buses, locomotives, ships, and heavy construction equipment.

The third type of power plant commonly used is the aircraft gas-turbine engine. This engine is rapidly replacing the spark-ignition engine on large commercial and military aircraft, although the latter engine is still the primary power source for light aircraft. The gas turbine is used to a very limited extent in experimental or test installations on railroad locomotives in passenger service only. Use of the gas turbine to power large truck-tractors

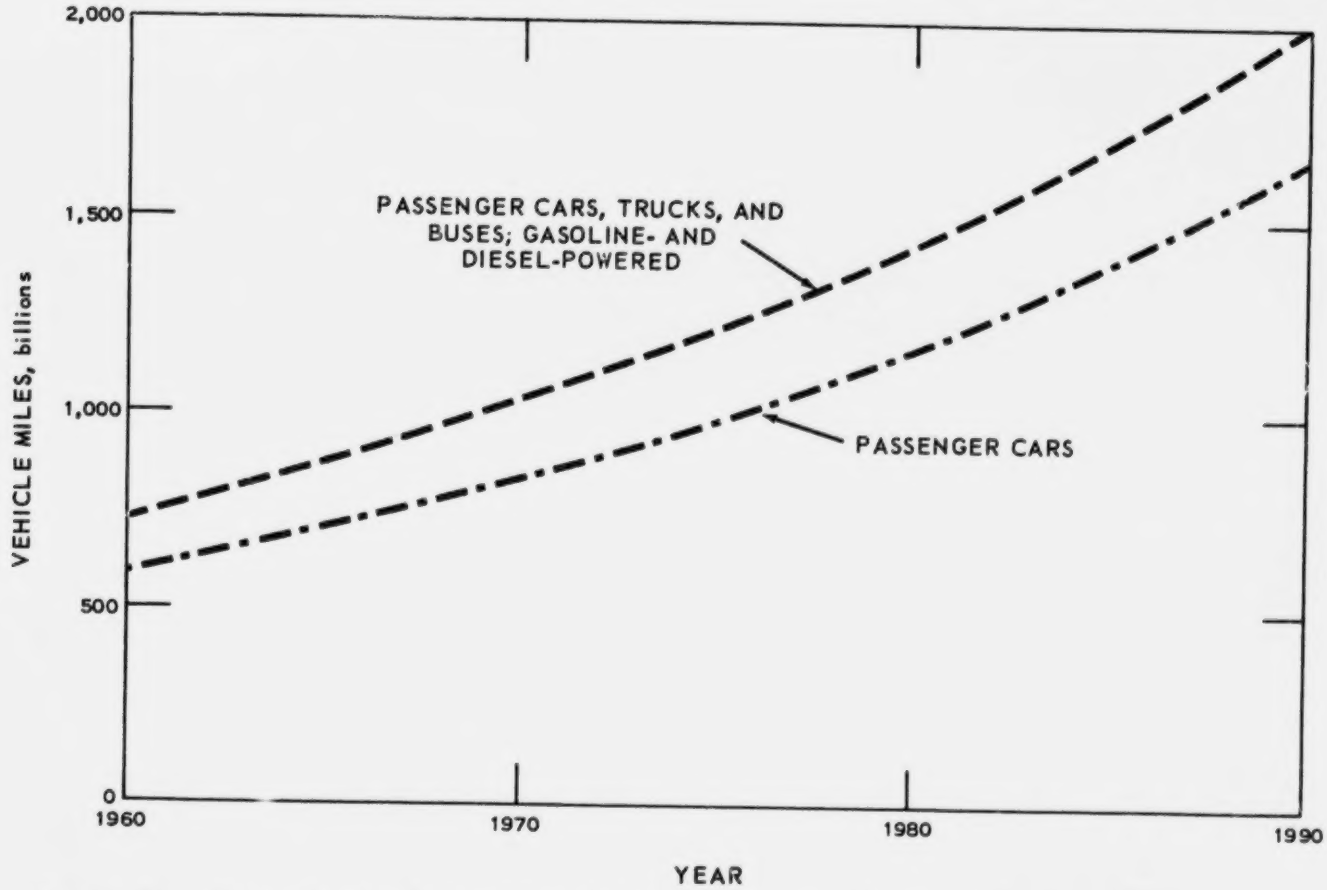

Figure 2-1. Past and projected United States vehicle miles.[9] (Curve-fitted data for medium estimates in Reference 9)

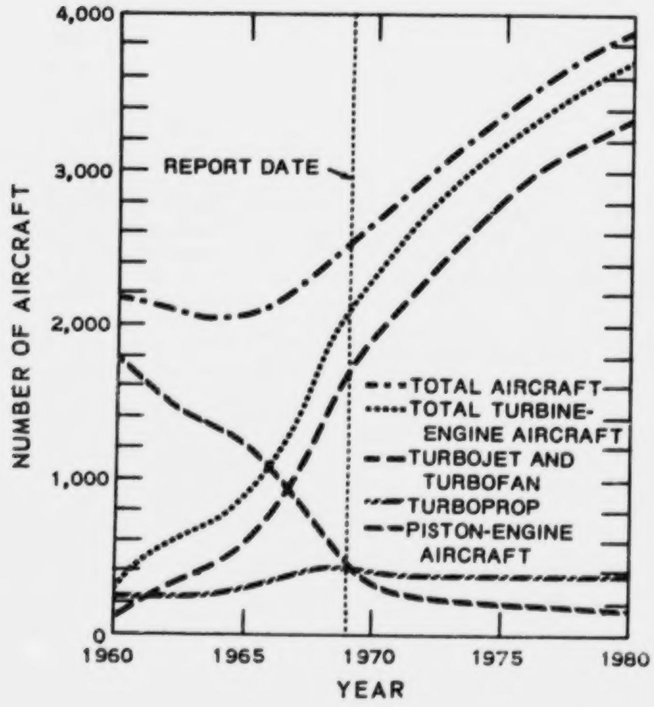

Figure 2-2. Composition of United States air carrier (commercial) fleet.[4]

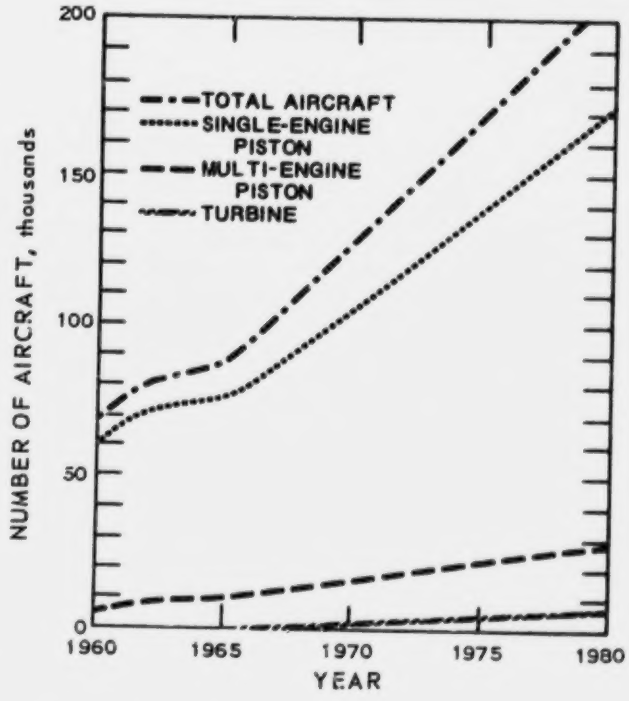

Figure 2-3. Composition of United States general aviation fleet.[4]

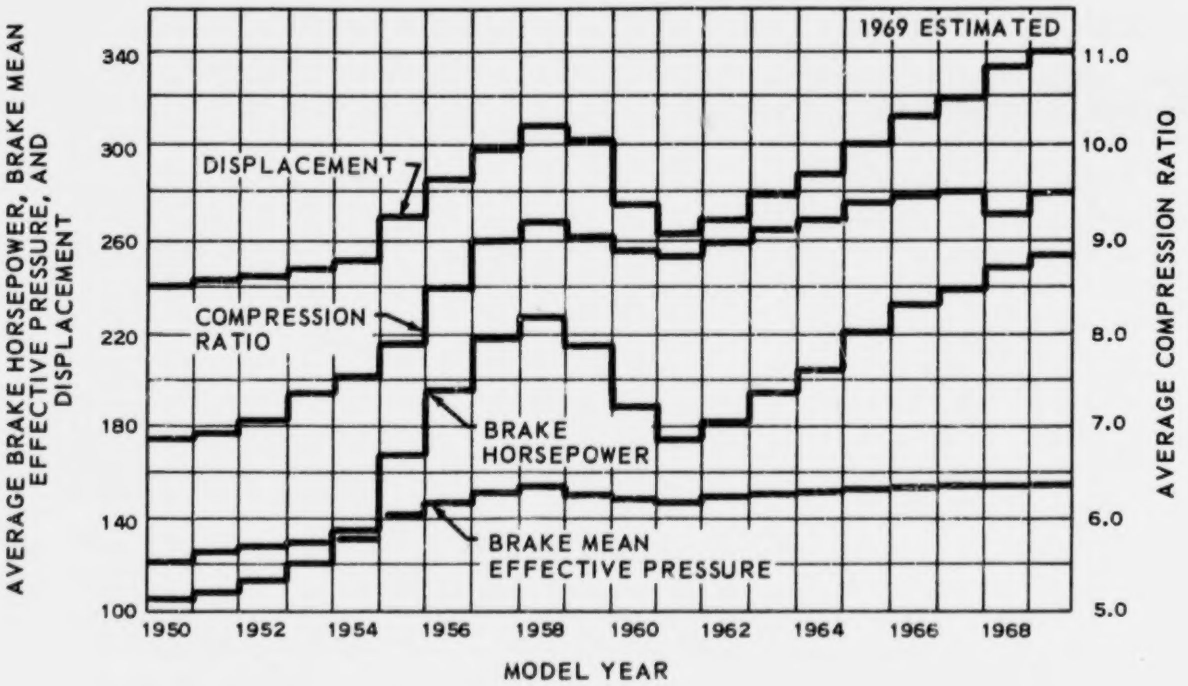

Figure 2-4. Trends of American passenger car engine design.[10] (Courtesy of Ethyl Corporation)

for cross-country hauling by 1971 is planned by one manufacturer.[11,12]

2.2.2.1 Spark-Ignited Piston Engine

The carbureted four-stroke, Otto-cycle, gasoline engine is commonly available in various configurations, such as in-line four- and six-cylinder, V-6, V-8, and horizontally opposed four- and six-cylinder.

The operating cycles of all are basically similar (Figure 2-5). A piston moves up and down in a cylinder, transmitting its motion through a connecting rod to the crankshaft,

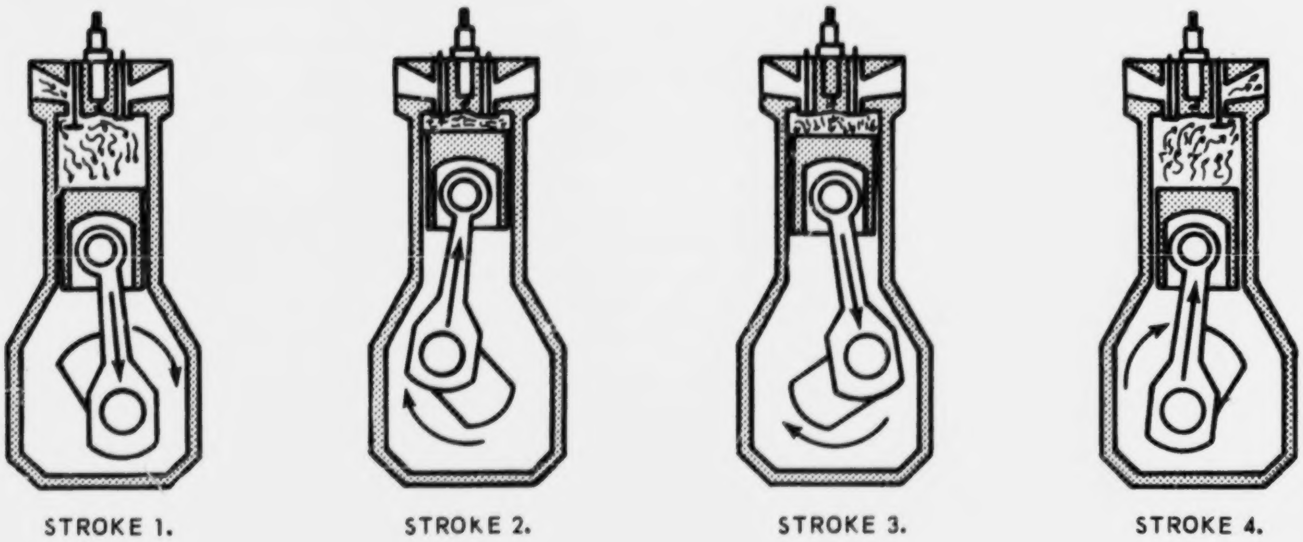

Figure 2-5. Schematic of four-stroke-cycle engine.

which drives the car through a suitable drive train.

The four strokes of the four-stroke-cycle engine are:

1. *Intake* - Descending piston draws charge through open inlet valve filling cylinder space.
2. *Compression* - Rising piston compresses charge against closed valves, spark plug fires, starting combustion.
3. *Expansion* - Burning mixture expands, forcing the piston down. This is the one stroke of the four that deliveres power.
4. *Exhaust* - With the exhaust valve open, the rising piston forces products of combustion out of cylinder.

Two-stroke-cycle engine operation is indicated by Figure 2-6. The poppet valves are usually replaced by ports, especially on small engines, which are opened and closed by the movement of the piston, although two-stroke-cycle engines sometimes use valves to open and close the exhaust ports. Two-stroke-cycle engines are not used on any passenger cars manufactured in the United States; they are, however, commonly used for motorcycles and motor scooters, small gasoline utility engines, and outboard motors. The phases of the two-stroke cycle are:

1. *Intake* - With transfer and exhaust ports open, air under slight pressure in crankcase flows into engine cylinder.
2. *Compression* - Rising piston covers ports, compresses charge in cylinder, creates vacuum in crankcase. Spark plug fires.
3. *Expansion* - Burning fuel expands, pushing piston down. Air flows into crankcase, to be compressed as the piston descends.
4. *Exhaust* - Descending piston uncovers exhaust port. Slight pressure builds up in crankcase, enough to move air into cylinder.

Some two-stroke-cycle engines are fitted with an air-box that serves the same purpose as the crankcase in the preceding discussion.

The carburetor used on current four-stroke-cycle, light-duty vehicles, provides the correct air-fuel ratios for best performance and fuel consumption across the vehicle speed and load range. The air-fuel mixture in the engine must be within a rather narrow band of ratios

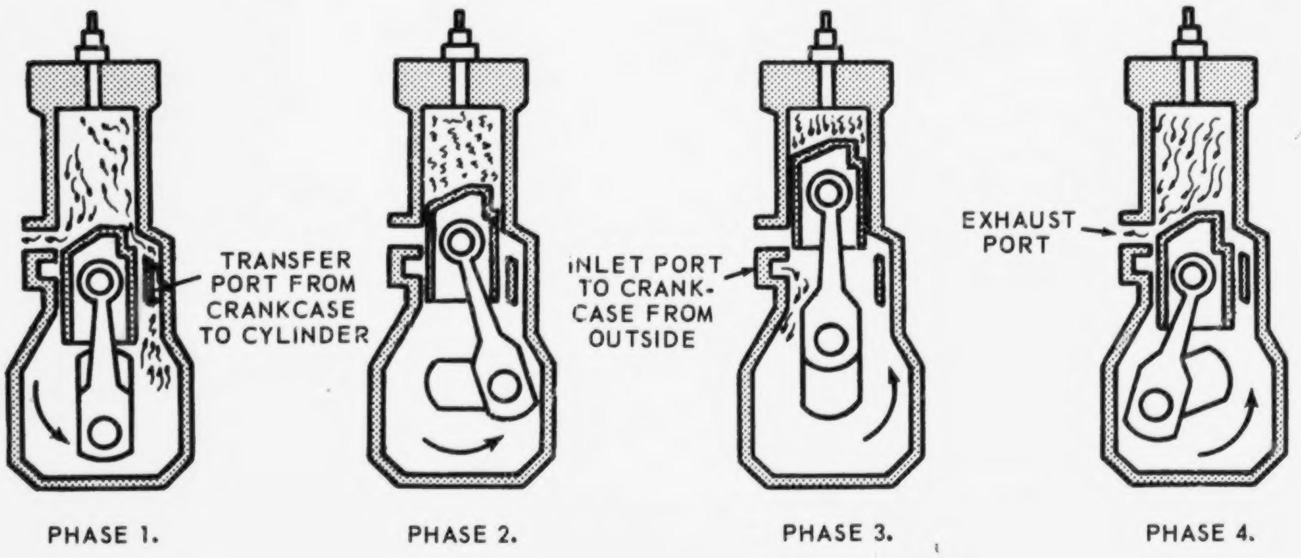
TRANSFER PORT FROM CRANKCASE TO CYLINDER
INLET PORT TO CRANK-CASE FROM OUTSIDE
EXHAUST PORT
PHASE 1.
PHASE 2.
PHASE 3.
PHASE 4.

Figure 2-6. Schematic of two-stroke-cycle engine.

in order to be combustible. This band generally encompasses air-fuel ratios of between about 9 and 17 pounds of air per pound of fuel. Best fuel economy is obtained when all cylinders receive a ratio slightly leaner than stoichiometric, but best power output is obtained at ratios that are slightly fuel-rich. (Figure 2-7).

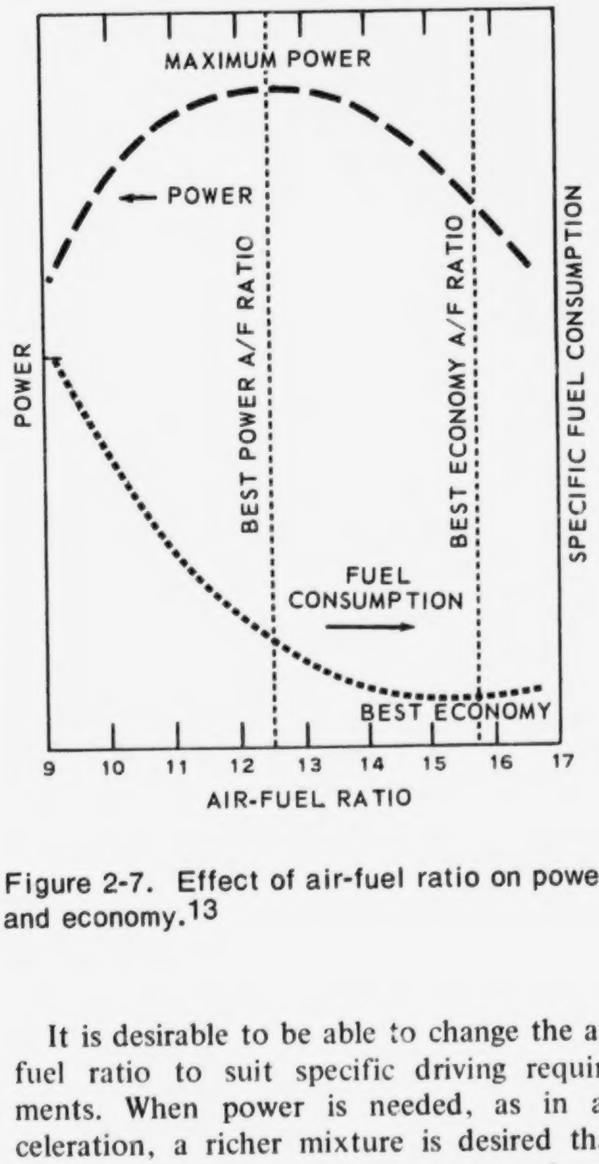

Figure 2-7. Effect of air-fuel ratio on power and economy.[13]

It is desirable to be able to change the air-fuel ratio to suit specific driving requirements. When power is needed, as in acceleration, a richer mixture is desired than during steady-state cruise, where a leaner mixture can be used to achieve greater economy. At open-throttle conditions during low speed acceleration, the maximum octane requirement of an engine can be lowered by enriching (reducing) the air-fuel ratio. This is a phenomenon that is considered in carburetor and engine design.

The ignition system is designed to ignite the air-fuel mixture at the precise instant at which conditions are optimum for best power. As engine speed increases, the time of ignition must be advanced to a point on the compression stroke before top dead center (i.e., earlier). Again, a compromise must be made under high-load conditions to reduce octane number requirement. To accomplish this, the spark is retarded slightly (i.e., later in the compression stroke) from best power.

The distributor shaft has centrifugal weights attached to it that advance the spark as engine speed increases. A pressure diaphragm, subjected to carburetor bore vacuum, senses engine air-flow and advances the spark as air-flow increases. Through these systems, the distributor senses engine speed and load and provides the proper spark advance for various driving conditions.

The exhaust system of the engine is made up of a manifold connected to each cylinder exhaust port, and piping to carry the gases to the rear of the vehicle, where they are discharged to the atmosphere. At some point between the manifold and the discharge, a muffler is used to quiet the exhaust noises.

2.2.2.2 Diesel (Compression-Ignition) Engine

Diesel (or compression-ignition) engines use either the two- or the four-stroke cycle, as described for the spark-ignition gasoline engines. The method of ignition and the fuel systems differ for the diesel engine, however. The fuel does not enter the cylinder as a mixture with air, but is injected under high pressure into the chamber in precise quantities through precision nozzles. As the piston nears the top of the cylinder on the compression stroke, the air charge is compressed to a high pressure and a high temperature. Fuel injected into this high temperature air ignites without the aid of a spark. Ignition timing is controlled by timing the injection of the fuel. Unlike the gasoline engine, in which power output is regulated by airflow control, power output of the diesel engine is controlled by the amount of fuel injected for each cycle.

When the engine is operating within its normal design limits (maximum rated power or less), the overall air-fuel mixture is much leaner than for a spark-ignition engine. Air is always delivered to the cylinders in excess of quantities necessary for complete combustion of the fuel. Because of this excess air, and the high temperature in the combustion chamber, the diesel engine is inherently low in CO emissions.

The advantages of the diesel engine, i.e., relatively low emissions of CO and relatively good fuel economy, are offset by other factors that have discouraged its use in passenger cars. These include:

1. High weight-to-power ratio - The high compression ratio necessary to achieve compression ignition requires more rugged construction for the diesel than for the spark-ignition engine.
2. Noise - High rates of pressure-rise during combustion make the diesel noisy relative to a spark-ignition engine.
3. Large size for comparable power - The maximum speed of diesel engines is generally lower than that of gasoline engines because of the difficulty in getting efficient combustion at high speeds. Thus, a larger diesel engine is required to produce the same amount of power that could be obtained from a smaller, higher-speed, spark-ignition engine.
4. Cost - The requirement for rugged engine construction and precision fuel-injection equipment causes the diesel to be more expensive to manufacture than the spark-ignition engine.
5. Odor and smoke - Exhaust odor and smoke from diesel engines are generally considered more objectionable than those from spark-ignition engines.

2.2.2.3 Aircraft Gas Turbine Engine

Fundamentally, a gas turbine engine may be considered as consisting of four main sections: (1) a compressor, (2) a burner, (3) a turbine, and (4) a tailpipe (possibly having a jet nozzle). A conventional turbojet engine is illustrated diagrammatically in Figure 2-8a. The air entry section is fitted with a diffuser, and supplies air to a rotary compressor of the centrifugal or axial type, in which the air is compressed and delivered at a higher pressure and a higher temperature to one or more combustion chambers. There fuel is added and burned in primary combustion air, increasing the gas temperature to a maximum value. Secondary air is added to cool the gases, which then expand through a turbine wheel, converting some portion of the available energy of the gases into work. The work produced by the turbine must be sufficient to drive the compressor at the desired speed of rotation in order to produce the required air-flow for the thrust required. The energy available in the combustion gases far exceeds the work requirement of the compressor. The gases leave the turbine wheel with a large proportion of energy still available, and the gas pressure is still well above atmospheric. A suitably-designed exit nozzle releases the gases at high velocity, their momentum providing engine thrust.

Turboprop engines (Figure 2-8b) function in a similar manner, except that the jet thrust is held to a minimum. These relatively large turbines are designed to extract all of the power possible from the expanding gases to rotate the propeller and produce thrust.

The turbofan engine (Figure 2-8c) is much the same as the turboprop except that the propeller is replaced by a duct-enclosed, axial-flow fan. Engine thrust is developed by both the spinning fan and the jet thrust of the exhaust gases.

Turbojet engine performance is best at high altitude and high speed; fuel consumption is high at low airspeeds. The turboprop develops high thrust at low altitude, and has lower fuel consumption than the turbojet for comparable thrust. The turbofan lies between the two for low altitude thrust and fuel consumption, and is quieter than the turbojet.

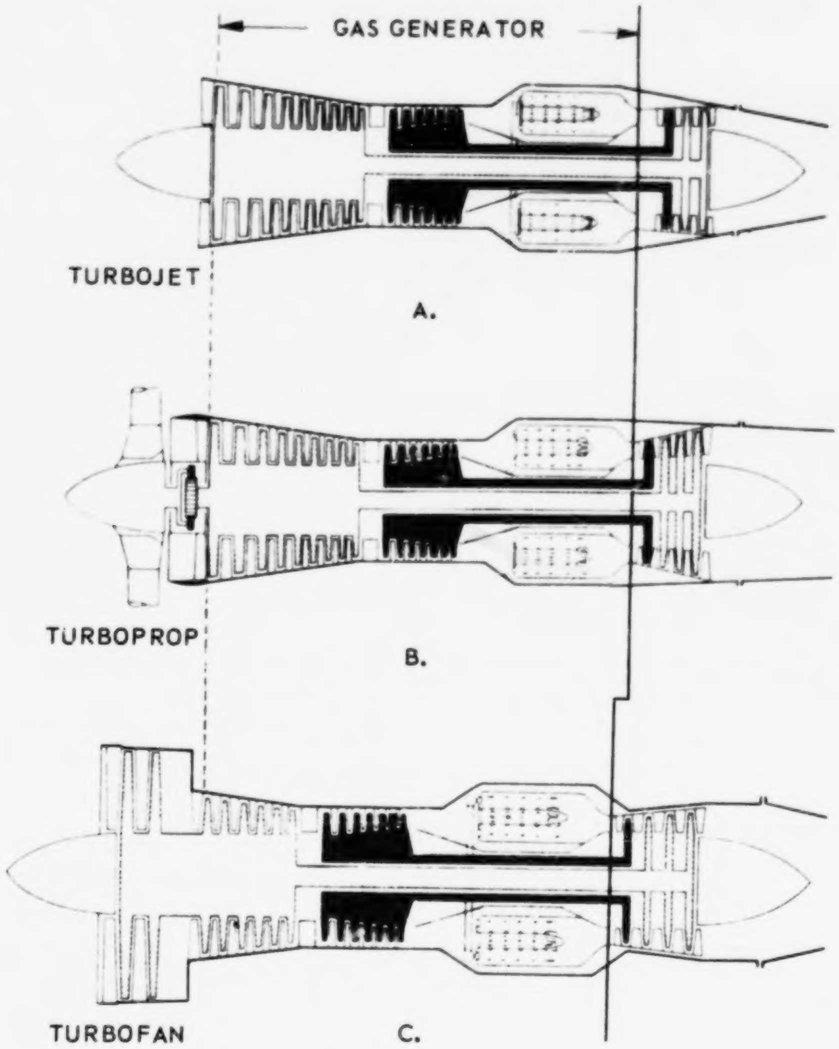

Figure 2-8. Views of three types of aircraft gas-turbine engines.[14]

2.2.3 Emissions

Contaminant emissions from a motor vehicle without emission controls originate from four sources: (1) the carburetor, (2) the fuel tank, (3) the crankcase, and (4) the engine exhaust. Hydrocarbon emission from the first source is the result of fuel vaporization during "hot soak" after shutdown. Vaporization from the tank occurs primarily when the fuel temperature in the tank increases. Crankcase emissions are the result of blowby past the piston rings. These emissions, unless controlled, escape to the atmosphere through the road draft tube or the crankcase ventilation cap. Hydrocarbons and CO appear in the exhaust gas as products of incomplete combustion. Oxides of nitrogen result from the reaction of the nitrogen and oxygen contained in the combustion air at the high temperature prevailing during combustion.

Figure 2-9 shows the approximate distribution of the emissions from a motor vehicle without any emission control devices.[15]

2.2.3.1 Nature and Formation of Emissions

When a hydrocarbon fuel is burned with the amount of air containing enough oxygen

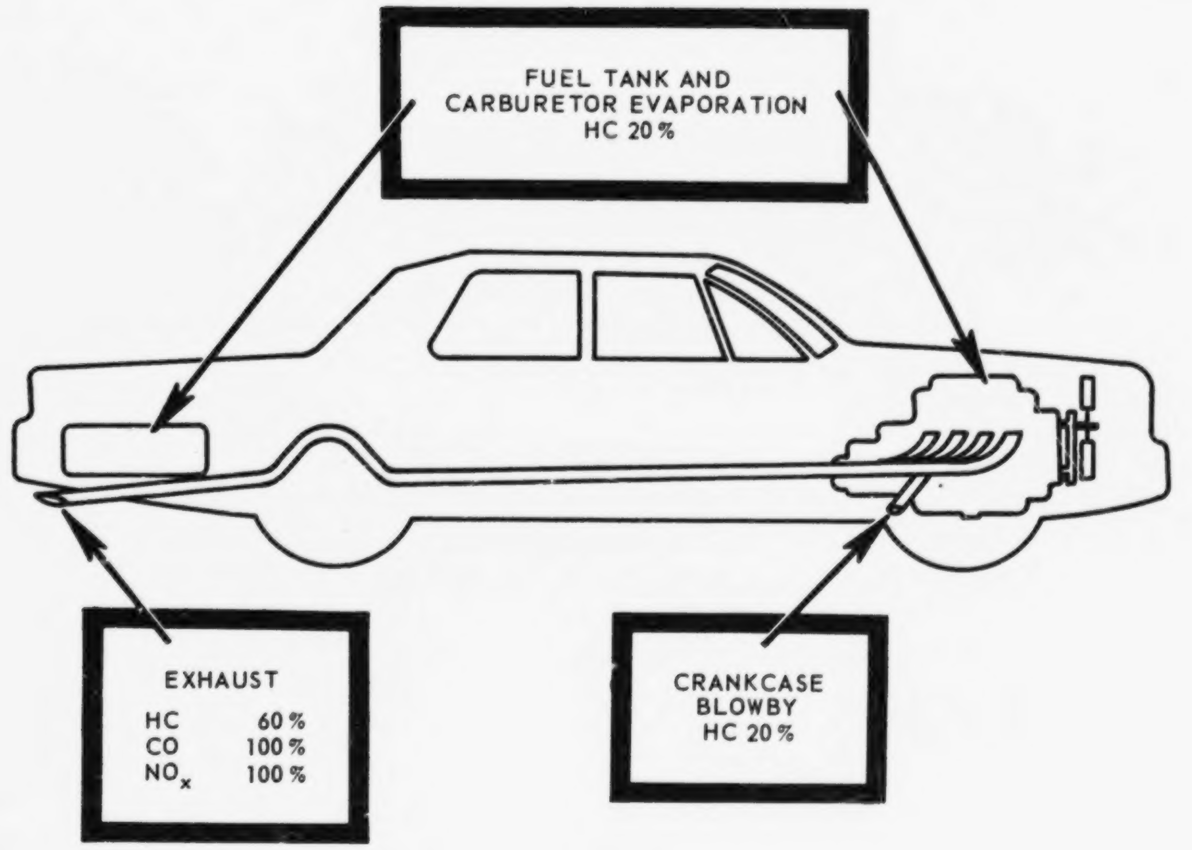

Figure 2-9. Approximate distribution of emissions by source for a vehicle not equipped with any emission control systems.[15]

to oxidize it completely, the following basic reaction might be assumed to occur:

$$1.00\,CH_{1.85} + 1.460\,O_2 + 5.50\,N_2 \rightarrow 0.925\,H_2O + 1.00\,CO_2 + 5.50\,N_2$$

This reaction incorporates the following assumptions:

1. Most hydrocarbon fuels are accurately represented as consisting of 1.85 hydrogen atoms per carbon atom ($CH_{1.85}$).
2. The volume ratio of nitrogen (N_2) to oxygen (O_2) in the air is 3.76:1.
3. The fuel is burned completely to water (H_2O) and carbon dioxide (CO_2).
4. Nitrogen is inert and does not react with any other substances in the combustion chamber.

Assumptions 1. and 2. are quite true in practice. The formation of CO, NO_x, and HC in the combustion process indicates that assumptions 3. and 4. are not wholly correct.

2.2.3.1.1 CO and hydrocarbons. Combustion of the carbon in the fuel proceeds (simplified) through the following steps:

$$2C + O_2 \rightarrow 2\,CO$$
$$2\,CO + O_2 \rightarrow 2\,CO_2$$

The first reaction proceeds at a much greater rate than the second. Hydrogen in the fuel is oxidized to H_2O quite easily, provided sufficient oxygen is available locally for combustion. Poor distribution and mixing of fuel and air (which is likely to occur to some extent when fuel droplets rather than fuel vapor are present) can result in incomplete combustion, and produce CO that is emitted in the exhaust gases. Although the overall air-fuel mixture may be stoichiometric, local conditions at a particular point in a combustion chamber may be far from stoichiometric. Such conditions of poor distribution are also conducive to increased hydrocarbon emissions.

Obviously, a fuel-rich (low air-fuel ratio) mixture introduces more fuel into the combustion chamber than can be completely burned, increasing emissions of CO and hydrocarbons. Also, an air-rich (high air-fuel ratio) mixture would provide excess air to partially offset the increased emissions that result from poor distribution and vaporization. The relatively large amount of excess air used in the diesel and gas turbine engines is the dominent reason for their relatively low emissions of CO and hydrocarbons.

Other factors may also contribute to increased emissions. One of these is the quenching of the flame at the relatively cool combustion chamber boundaries. Quenching can occur even if the fuel is perfectly vaporized and distributed throughout the chamber and is well established as the most significant mechanism leading to exhaust hydrocarbon emissions in properly designed spark-ignition engines.[16]

Gross malfunction of the ignition or fuel induction systems can increase emissions of CO and hydrocarbons from spark-ignition engines. A misfire allows an entire air-fuel charge to be emitted. An automatic choke sticking closed or a very dirty air cleaner element can reduce air-fuel ratio, generally increasing emissions of CO and hydrocarbons.

Chemical equilibrium phenomena should be considered in a discussion of the formation of CO and hydrocarbons. Combustion reactions are somewhat reversible at high temperatures, indicating that products and reactants can exist in equilibrium at high temperatures. This partial reversal of combustion reactions at high temperature is known as dissociation.

If the equilibrium mixture is cooled rapidly (as it is by rapid expansion), it may be "frozen", meaning that its composition is unable to change, even though equilibrium considerations indicate that dissociation should be greatly reduced as the temperature is reduced. The rapid lowering of temperature and the accompanying decrease in the rate at which the mixture approaches the new low-temperature equilibrium, are responsible for the freezing of the composition of the mixture.

2.2.3.1.2 NO_x. Equilibrium considerations are very important in the discussion of the formation of NO_x. The reaction

$$N_2 + O_2 \rightleftarrows 2\ NO$$

indicates that nitrogen may be oxidized to nitric oxide (NO) and exist in equilibrium with N_2 and O_2. The concentration of NO which may exist (theoretically) is significant only at high temperatures. This means that N_2 and O_2 do not unite to form a significant concentration of NO at low temperatures. Rapid cooling (as discussed in Section 2.2.3.1.1) can occur, however, and "freeze" the mixture with a relatively high concentration of NO. Generally, the higher the flame temperature to which air is exposed, the higher will be the resulting NO concentration after rapid cooling. The rate of reaction of NO back to N_2 and O_2 is very low at low temperatures, even though equilibrium considerations favor the reaction.

It is essential to understand the difference between chemical kinetics, which involve the rate at which chemical reactions proceed (which is influenced by temperature), and chemical equilibrium, which involves theoretical concentrations of products and reactants as a function of temperature (and pressure for some reactions), without any consideration of the time which may be required to achieve equilibrium as conditions of temperature (and pressure) change.

From the preceeding discussion, it is apparent that NO_x emissions could be minimized by:

1. Reducing the flame temperature during combustion of air-fuel mixtures.

2. Providing insufficient oxygen to oxidize N_2.
3. Expanding (cooling) the mixture of combustion products at a slow rate which would allow NO to reform N_2 and O_2.

One of the most effective methods for reducing both flame temperature and the amount of oxygen available is to reduce the air-fuel ratio. A fuel-rich mixture burns at a lower temperature than a stoichiometric mixture because heat that could otherwise be used to heat the gases in the combustion chamber must be used to heat excess fuel.

Since oxidation of carbon to CO occurs at a greater rate than oxidation of CO to CO_2, and because combustion of a mole (specific number of molecules) of carbon to CO releases less heat than combustion of a mole of CO to CO_2, burning of a fuel-rich mixture results in a lower heat release than burning of a stoichiometric mixture. The overabundance of fuel leaves little oxygen available to react with nitrogen. This rich-mixture approach would minimize NO_x emissions at the expense of greatly increased emissions of CO and hydrocarbons unless further measures were taken to control them specifically.

When a high air-fuel ratio charge is burned, much oxygen is available for oxidation of N_2, but the effect of low-flame temperature—resulting from the heating of excess air that does not enter into the combustion reactions—predominates, and reduces NO_x emissions. Presently available spark-ignited, gasoline-fueled engines exhibit poor performance under such conditions, however, probably because of the low velocity of flame propagation through a fuel-lean mixture, resulting in reduction of thermal efficiency. Operation at fuel-lean conditions can damage exhaust valves, and may cause backfiring through the carburetor at very high air-fuel ratios.

Other engine variables influencing the NO_x concentration in spark-ignited engine exhaust gas are:[17,19]

1. Spark timing - Advancing the spark usually increases the oxides of nitrogen by increasing peak combustion temperature.
2. Engine speed - Increasing speed while advancing the spark and at constant or increasing torque (decreasing manifold vacuum) promotes NO_x formation with either lean or rich mixtures by allowing less time for the products of combustion to expand and approach equilibrium at a lower temperature. Increasing engine speed, however, while maintaining constant power and decreasing torque may tend to decrease NO_x formation by depressing combustion pressure and temperature. The fact that power is proportional to the product of torque and speed suggests that it may be possible to "optimize" the engine characteristics for the lowest NO_x emissions at a given power level.
3. Compression ratio - Higher compression ratios, which increase peak combustion pressure and temperature, favor formation of NO_x, particularly under lean-mixture conditions.
4. Fuel distribution - NO_x concentration for a particular cylinder depends on the air-fuel ratio in the cylinder. Poor mixture distribution resulting in a near stoichiometric mixture in only a few cylinders of an engine causes a relatively large increase of NO_x for the entire engine.
5. Coolant temperature - Raising the coolant temperature tends to increase NO_x concentration.
6. Combustion chamber deposits - A greater deposit accumulation may increase NO_x concentration.

The high compression ratio of the compression-ignition (diesel) engine results in a high combustion temperature conducive to NO_x emissions. The gas turbine may prove to have the inherent capability for low NO_x emissions.[20] Combustion at fuel-lean conditions in the primary zone, followed by dilution of combustion gases with secondary air at an optimum rate in a long combustion chamber to approach equilibrium at the turbine inlet temperature, may greatly reduce NO_x emissions. The cooling of gases at an optimum rate in a reciprocating-piston, internal-combustion engine is difficult to achieve because engine speed inherently sets the rate of expansion.

2.2.3.2 Emission Reactivity

A discussion of emissions from mobile sources would not be complete without some reference to the concept of reactivity. This term describes the tendency of organic substances of certain chemical formulas and molecular structures to enter into chemical reactions in the presence of NO_x and ultraviolet radiation (sunlight) in the atmosphere more readily than substances of other formulas and structures.

Although rigid criteria of reactivity or the assignment of precise indexes of reactivity are not offered for the various organic substances at this time, several relative chemical reactivity scales have been suggested.[21-30] While these scales vary somewhat in detail, general trends are similar. In general, paraffinic hydrocarbons and acetylene exhibit the lowest reactivity. At the opposite extreme, olefinic hydrocarbons represent the most reactive class of hydrocarbons. References to hydrocarbon or organic emissions in this document refer to total emissions rather than reactive emissions, unless otherwise noted.

2.2.3.3 Emission Quantities

Estimates of nationwide emissions of CO, NO_x, and HC for the year 1968 are presented in Table 2-3. All major sources are included to

Table 2–3. 1968 NATIONWIDE EMISSION ESTIMATES[15]
[10^6 tons/year]

Category	HC	CO	NO_x
Transportation			
Motor vehicles			
Gasoline	15.2	59.0	6.6
Diesel	0.4	0.2	0.6
Aircraft	0.3	2.4	n
Railroads	0.3	0.1	0.4
Vessels	0.1	0.3	0.3
Nonhighway use of motor fuels	0.3	1.8	0.3
Fuel combustion in stationary sources			
Coal	0.2	0.8	4.0
Fuel oil[a]	0.1	0.1	1.1
Natural gas[b]	n	n	4.7
Wood	0.4	1.0	0.2
Solid waste disposal	1.6	7.8	0.6
Industrial processes	4.6	9.7	0.2
Miscellaneous	8.5[c,d]	16.9[c]	1.7[c]
Total	32.0	100.1	20.7

[a] Includes kerosene.

[b] Includes natural gas processing plants and transmission facilities, and liquefied petroleum gas (LPG).

[c] Includes emissions from agricultural burning, forest fires, structural fires, and coal refuse fires.

[d] Includes organic solvent evaporation and gasoline marketing.

n - negligible.

indicate the contribution of transportation relative to other sources. It is obvious that mobile sources are responsible for major portions of emissions of concern in this document. Estimated total tonnages for the three emissions from gasoline-powered passenger cars and trucks as a function of year are shown graphically in Figures 2-10 through 2-12. The effects on the quantity of a single emission by imposition of a constant emission standard, assimilation of vehicles with emission control systems into the composite vehicle population, and vehicle population growth are illustrated by the curves for CO and hydrocarbons. Increases in emissions from 1960 to 1967, due to increase in vehicle population, are arrested and turned down during the period of 1967 to about 1980 by the increase in numbers of vehicles equipped with emission control systems and withdrawal of older cars from the vehicle population. Emission increases resume in the early 1980's, to again achieve rates of increase corresponding to growth of the vehicle population. National emissions of NO_x will continue to rise (having increased with efforts to control CO and hydrocarbons) with increasing vehicle miles, unless they are specifically controlled.

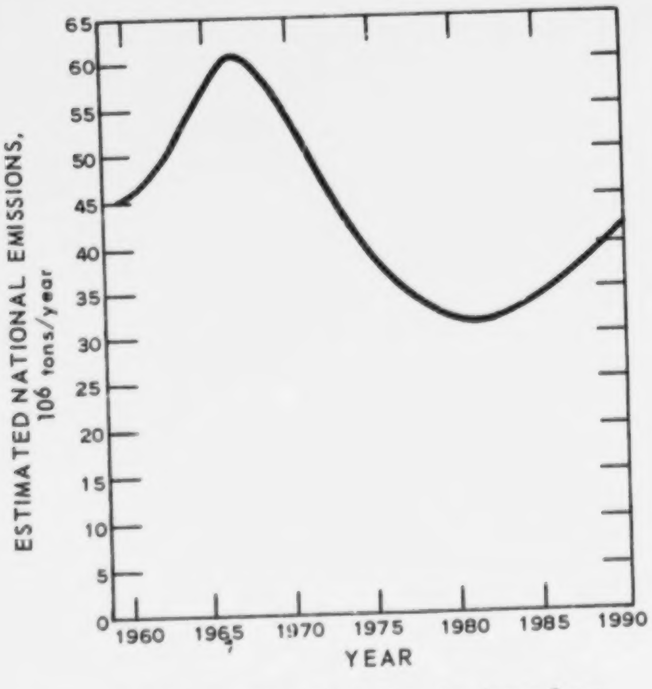

Figure 2-10. Estimated CO emissions from gasoline-powered automobiles and trucks through 1990 if Federal standards as of 1971 remain unchanged. Total urban and rural data used.[15]

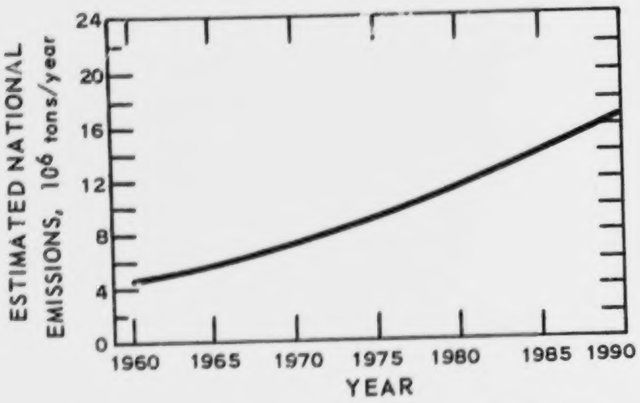

Figure 2-11. Estimated NO_x emissions from gasoline-powered automobiles and trucks through 1990 if Federal standards as of 1971 remain unchanged. Total urban and rural data used.[15]

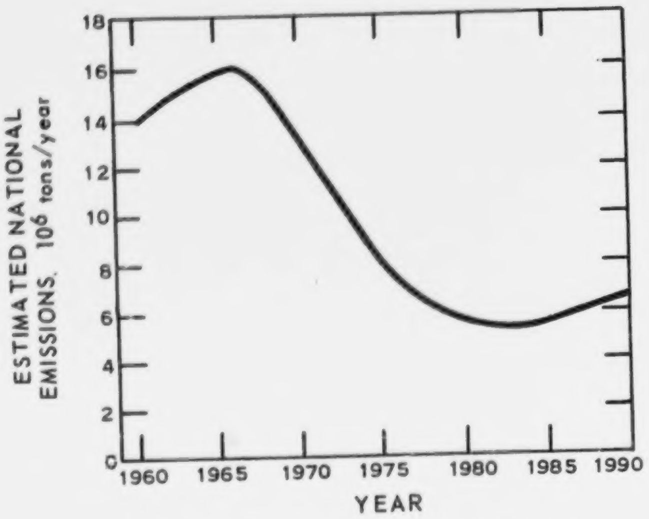

Figure 2-12. Estimated HC emissions from gasoline-powered automobiles and trucks through 1990 if Federal standards as of 1971 remain unchanged. Total urban and rural data used.[15]

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3. FEDERAL EMISSION CONTROL PROGRAM

3.1 LEGISLATION

Title II of the Clean Air Act, as amended,[1] is the legislative basis for the Federal air pollution control program for new motor vehicles. Federal Government action was preceded, however, by acts of the State of California.

Because of the early occurrence and intensity of its air pollution problem, California has pioneered in legislation and activities associated with control of vehicle emissions. The basic legislation for air pollution control in the State was enacted in 1947, in the form of enabling legislation to permit local jurisdictions to cope with specific pollution control problems.[2,3] The occurrence of air pollution in other areas of the United States emphasized the need for action on a nationwide scale.[4] In 1955 the Air Pollution Control Act[5] was enacted by the U.S. Congress to authorize a program for research and technical assistance for control and abatement of air pollution by the Secretary of Health, Education, and Welfare and the Surgeon General of the Public Health Service. The act recognized the primary responsibilities and rights of the states, local governments, and other public agencies in controlling air pollution, but provided grants to those agencies concerned with air pollution control for assisting them in the formulation and execution of their abatement research programs.

Emphasis on vehicular air pollution emerged with legislation in California from 1957 to 1960, and, nationally, in 1960. In 1959[3,6,7] the State Legislature required the Department of Public Health to develop and publish before February 1, 1960, standards for the quality of air and emission of exhaust contaminants from motor vehicles. The emission standards were based on a "rollback"[8] technique that was intended to reduce hydrocarbon emissions from the total vehicle population to the levels emitted by the total vehicle population in California in 1940. In 1960 the California Motor Vehicle Pollution Control Act was enacted; it created the Motor Vehicle Pollution Control Board (MVPCB) to implement the emissions standards adopted in 1959.[2,3,6,7] The Act made the Board responsible for issuing certificates of approval for motor vehicle pollution control devices, and stipulated that 1 year from the date on which two or more control devices were certified, all new cars registered in the State would be equipped with such devices. The Department of Health also adopted blowby standards.

The Schenck Act[9], enacted by the U.S. Congress in 1960, directed the Surgeon General of the Public Health Service to make a study and report to Congress within 2 years on the discharge of substances into the atmosphere from the exhaust of motor vehicles.

In 1961 the MVPCB approved a number of blowby control devices, and these controls thus became mandatory for new cars sold in California beginning with the 1963 model year.[7] The U.S. auto manufacturers, however, installed them voluntarily on new cars sold in California beginning with the 1961 models.

Also in 1961, an exhaust emission-control test procedure was developed and adopted, using 7- and 11-mode driving cycles, and requiring satisfactory operation of emission control systems for 12,000 miles.[10] During the period 1961 to 1963, the Board invoked an odor criterion pertaining to vehicle emissions which stimulated development of closed-crankcase emission-control systems. Garages and mechanics were licensed to install and service the open-crankcase emission control system in use at that time.[11]

In July 1962 the report of the Surgeon General to the Congress, directed by the Schenck Act, was approved by joint resolution of the U.S. House of Representatives and the Senate.[12] Its content is divided into three parts:

Part I summarizes then-current information and theories of the nature of air pollution resulting from emissions from motor vehicles, and examines approaches to the reduction of such pollution and some of the problems associated with control measures.

Part II reviews information that had been reported concerning the influence of air pollution on health, with particular reference to the effects of pollution arising from operation of motor vehicles.

Part III describes how motor vehicle operation relates to emissions of contaminants, the magnitude of the pollution problem, the nature of chemical reactions in the atmosphere, factors affecting concentrations, methods for reducing pollution, and the subject of ambient air quality and emission standards.

Late in 1963, the 88th Congress passed the Clean Air Act,[13] which replaced the 1955 Air Pollution Control Act. Among the provisions of this Act, a section on "Automotive Vehicle and Fuel Pollution" was particularly indicative of the continued and increasing concern for the problem of motor-vehicle-related air pollution. This section pertained to continued efforts by the automotive and fuel industries to control motor vehicle emissions. To encourage such efforts, the Secretary of Health, Education, and Welfare was directed to appoint a technical advisory committee composed of representatives of industry and the Department of Health, Education, and Welfare, to meet as directed by the Secretary, and to evaluate progress and recommend research toward devices and fuels to control automotive vehicle emissions. The Secretary was further directed to report semiannually to Congress on measures taken toward resolution of the vehicle exhaust emissions problem, including:

1. Occurrence of pollution as a result of the discharge of contaminants from automotive exhausts.
2. Progress of research into development of devices and fuels to reduce emissions from exhausts of automotive vehicles.
3. Criteria on effects of contaminant matter discharged from automotive exhausts.
4. Efforts to improve fuels so as to reduce emissions of exhaust contaminants.
5. Recommendations for additional legislation, if necessary, to regulate the discharge of contaminants from automotive exhausts.

In 1964 the California MVPCB approved exhaust emission control devices for new automobiles, which became effective with the 1966 model year cars.[7] It also adopted more stringent HC and CO exhaust standards for 1970 model cars; adopted standards for crankcase, fuel tank, and carburetor emissions; and issued a policy statement that standards for NO_X were needed and that the Board would consider in 1965 adoption of an exhaust standard for nitrogen oxide.

In 1965 the California requirement for installation of crankcase emission control devices on 1950 to 1960 model cars was relaxed in favor of Senate Bill 317, which required installation of such devices on only 1955 to 1960 models in certain counties when the vehicle is sold and reregistered.[6] The MVPCB specified reestablishment of deterioration factors based on 50,000 miles instead of 12,000, and required certification of each size engine instead of permitting averaging of all sizes of one make.[14]

Also in 1965 Congress amended the Clean Air Act to include a section known as the Motor Vehicle Air Pollution Control Act,[15] which directed the Secretary of Health, Education, and Welfare to prescribe standards applicable to exhaust emissions from new motor vehicles or new motor vehicle engines, and to issue certificates of conformity for vehicles and engines conforming with those standards. The Act also directed the Secretary to conduct and accelerate programs relative to hydrocarbon evaporative losses and NO_x and aldehydes from gasoline-powered or diesel-powered vehicles, and provided for constructing, equipping, and staffing facilities necessary to carry out the authorized actions.

In 1966 U.S. standards for crankcase emissions and hydrocarbon and CO exhaust emissions, and procedures for determining compliance with such standards, were published; they applied to all 1968 model automobiles.[16] U.S. auto manufacturers, however, had installed crankcase devices voluntarily throughout the country beginning with the 1963 models. The standards for the 1968 and subsequent models required the use of a "closed" crankcase ventilation system in place of the open system which had been employed on a voluntary basis. (See Section 5.1.1 for a discussion of open and closed systems.)

In 1967 California adopted test procedures for emission control systems for mobile internal combustion engines used inside buildings,[17] and passed the Pure Air Act of 1967, to become effective in November 1968.[18] Features of the Act included:

1. Provisions for adoption of low emission standards for new state vehicles more stringent than the approved test standards for public vehicles.
2. Adoption of test procedures for the approval of new motor vehicles based upon emission standards specified in the Act, bringing the California procedures into conformance with the Federal.
3. Adoption of regulations for the approval of devices for used motor vehicles, based upon their emissions.
4. Adoption of regulations specifying the manner in which motor vehicles on factory assembly lines are to be emission tested.
5. Adoption of exhaust emission standards for hydrocarbons, CO, and NO_x for new diesel-powered vehicles no later than January 1, 1971, applicable no later than January 1, 1973.
6. Adoption of emission standards for motor vehicles not now covered.
7. Requirement that manufacturers of vehicles report their work relative to control of oxides of nitrogen for their vehicles.
8. Establishment of exhaust emission standards and effective dates for those standards, beginning in 1970, for hydrocarbon, CO, and NO_x for gasoline-powered cars, trucks, truck-tractors, and buses; diesel-powered vehicles, and for fuel evaporative losses from gasoline-powered vehicles.

Late in 1967, Congress enacted Public Law 90-148, an amendment to the Clean Air Act of 1963. In addition to continuing all major activities which the Department of Health, Education, and Welfare was authorized to conduct, it provided the basis for systematic control activities on a regional scale, hinging on state action to deal with air pollution problems within air quality regions designated by the Department. The states are responsible for setting air quality standards for such regions and for developing plans to meet those standards. The Department of Health, Education, and Welfare assists the states by publishing air quality criteria and information on the status and cost of recommended techniques for preventing and controlling air pollution, including cost-effectiveness of alternative methods.

The Act explicitly provides for preemption by the Federal Government concerning establishment of standards for emissions from new motor vehicles and engines. It provides, however, that this preemption may be waived upon application by any state which has adopted standards other than crankcase emission standards prior to March 30, 1966. Practically, this stipulation limits application for waiver to the State of California. The Act further provides that any state or political subdivision has the right to otherwise control, regulate, or restrict, the use, operation, or movement of registered or licensed vehicles.

State maintenance and/or inspection programs may be assisted by grants to state air pollution control agencies for up to two-thirds of the cost of developing uniform motor vehicle emission device inspection and emission testing programs. Any such grant can be made only if the Secretary of Transportation certifies that the program is consistent with any highway safety program established pursuant to the Highway Safety Act.

Standards for exhaust emissions, fuel evaporative emissions, evaporative losses, and smoke emissions, applicable to 1970 and later vehicles and engines, were published in the Federal Register.[19]

In 1968, the California Pure Air Act of 1968 became effective, but waiver of Federal preemption by the Secretary of Health, Education, and Welfare was necessary before the more stringent California emission standards could be adopted. In response to California's application, a waiver was granted[20] in May 1969.

In December 1969, The Federal Register[19] notice applicable to 1970 and later vehicles and engines was amended[21] to include labeling by the manufacturer of each gasoline-powered, light-duty vehicle as conforming to U.S. DHEW regulations for new motor vehicles. This provision is effective February 10, 1970 and requires also that engine tune-up specifications be included on the label (see Section 3.2.2).

3.2 REGULATIONS

3.2.1 Emission Standards

3.2.1.1 General

Table 3-1 represents the sequence in which California and Federal emission standards for motor vehicles became effective, or are to become effective, through provision of devices and systems to control emissions in compliance with these standards. In general, the tabular data represent standards for those gasoline-powered motor vehicles and motor vehicle engines constituting a majority of the vehicle population. (Standards for diesel engines are to be adopted in California by January 1, 1971, and are to become effective by January 1, 1973.) Footnotes cover some of the additional information necessary to portray the standards adequately, and references provide more detail. The data suggest the manner in which control effectiveness in California preceded the national program for vehicular emission control, but do not indicate the extent to which development of California standards led Federal regulation. Exhaust emission standards applicable to 1966 model motor vehicles sold in California, for example, were adopted in 1959, whereas comparable Federal standards applicable to 1968 models were published in 1966. In this and other instances, the time lapse between adoption of standards and compliance with them in California has been influenced by the regulation which made installation of a system mandatory 1 year after two or more such systems or devices have been certified as complying with an emission standard.

Applicability to specific types of vehicles and engines varies between California[22] and Federal[16,19] hydrocarbon and CO emission standards. Both, however, currently apply to gasoline-powered motor vehicles and motor vehicle engines. Neither applies to engines of less than 50 cubic inches (810 cc) displacement, nor to such vehicles as motorcycles, motor scooters, marine craft, aircraft, locomotives, lawntending equipment, and construction machinery. With certain exceptions, depending on model year and vehicle type, notably pre-1966 models, California regulations with respect to crankcase and exhaust emissions apply to every passenger vehicle, except motorcycles. In addition, they apply to trucks, truck-tractors, and buses, provided they are not diesel-powered. Federal

Table 3–1. SEQUENCE OF CALIFORNIA AND FEDERAL GASOLINE-POWERED VEHICLE EMISSION STANDARDS FOR CO, NO_x, AND HC[1,12,17-20]

Emission	Standards according to date of compliance						
	1963	1966	1968	1970	1971	1972	1974
California							
Crankcase	0.15%[a]	0.10%[a]					
exhaust							
HC		275 ppm		2.2 g/mi[b] (180 ppm)		1.5 g/mi[b]	
CO		1.5%		23 g/mi[b] (1.0%)			
NO_x as NO_2					4.0 g/mi[b]	3 g/mi[b]	1.3 g/mi[b]
Evaporative				6g/test			
Federal							
Crankcase			0.0%				
exhaust							
HC			275 ppm[c]	2.2 g/mi[d]			
CO			1.5%[c]	23 g/mi[d]			
NO_x as NO_2							
Evaporative					6 g/test[e]		

[a] Emission is stated as a percent of fuel supplied.

[b] For vehicles less than 6001-lb gr wt. Standards for heavier vehicles are:

Year	1970	1972
HC	275 ppm	180 ppm
CO	1.5%	1.0%

[c] For engines over 140 cu in. For smaller engines, standards are:

Displacement	50 to 100 cu in.	101 to 140 cu in.
HC	410 ppm	350 ppm
CO	2.3%	2.0%

[d] For light-duty vehicles. For heavy-duty gasoline engines, standards are HC, 275 ppm; CO, 1.5 percent.

[e] Does not apply to off-the-road utility vehicles until 1972.

standards apply only to 1968 and later model motor vehicles and motor vehicle engines. For 1968 and 1969 model years, the regulations apply to all new vehicles and vehicle engines (except commercial vehicles over ½-ton and motorcycles, and their respective engines). Beginning with 1970 models, applicability is differentiated between "light-duty vehicles" (6,000 lb gross weight or less) and engines for "heavy-duty vehicles" (over 6,000 lb gross weight).

Beginning with 1970 standards, vehicle exhaust emissions from light-duty vehicles are expressed in mass terms (grams per mile) rather than in terms of concentration (fraction of total exhaust). Exhaust emissions from heavy-duty vehicles continue to be expressed in terms of concentration. A single, median concentration standard may give no credit to the small motor vehicle engine, or may falsely credit the large engine insofar as total mass emissions are concerned. Pre-1970 standards attempted to avoid this inequity by allowing higher emission concentrations for smaller engines as shown in Table 3-2.

3.2.1.1 *Prospective: Conventional Gasoline Engine*

As the greatest single contributor to production of CO, NO_x, and hydrocarbons

Table 3–2. ALLOWABLE EMISSION RATES UNDER 1968 FEDERAL STANDARDS[16]

Engine displacement, cu in.	Average maximum allowable emissions	
	CO, %	Hydrocarbons, ppm
0-49	No limit	No limit
50-100	2.3	410
101-140	2.0	350
141 and over	1.5	275

from mobile sources the conventional gasoline-powered motor vehicle is receiving the greatest share of the effort toward emission control.

3.2.1.2.1 Hydrocarbons. Initially, crankcase emission standards in California permitted hydrocarbon emissions equivalent to 0.15 percent of supplied fuel. This was later reduced to 0.10 percent. The 1968 Federal standards allow no crankcase emissions. Maximum average exhaust hydrocarbon emission was initially specified as 275 ppm,* or 3.4 grams per mile (g/mile), and later reduced for 1970 model vehicles to 2.2 g/mile (or 180 ppm). The California standard to become effective in 1972 is 1.5 g/mile (120 ppm). Concentrations as low as 50 ppm (0.61 g/mile) are considered commercially feasible by 1975, and ultimately as low as 25 ppm (0.31 g/mile).[23] Control of evaporative losses is required in California with standards for 1970 models and nationally with standards for 1971 models.

3.2.1.2.2 CO. Carbon monoxide standards, as a part of vehicle emission standards for 1966 model cars in California and 1968 models nationally, permitted a maximum average concentration of 1.5 percent by volume of total exhaust, equivalent to 35 g/mile. With the 1970 models, the Federal and California standards become 23 g/mile (1.0 percent). A concentration as low as 0.5 percent (12.5 g/mile) is considered commercially feasible, and 0.25 percent (6.3 g/mile) is considered ultimately feasible.[23]

3.2.1.2.3 NO_X. Standards for exhaust emissions of NO_X become effective for the first time with the California standard of 4.0 g/mile in 1971 for vehicles under 6,001 pounds of gross weight, with successive reductions to 3.0 g/mile for the 1972 model year and 1.3 g/mile for the 1974 model year. Mass emission levels of NO_X for a vehicle with no emission controls are about 5 g/mile (see Table 3-3). With some control systems for exhaust HC and CO, however, NO_X emissions may tend to increase as CO and HC emissions decrease.

3.2.1.3 Prospective: Diesel Engine

By comparison with the effort expended with respect to the gasoline engine, very little has been done regarding control of hydrocarbon, CO, and NO_X emissions from diesel engines. California legislation[22] provides for adoption of standards for diesel engines in 1971, to become effective in 1973. Crankcase and evaporative emissions are extremely low for the diesel, its exhaust being essentially the only emission source.

3.2.2 Compliance

Testing for compliance with established standards is a prerequisite to the sale of new motor vehicles. California procedures for approving devices for emission control were established early in its vehicle emission control program, and have been developed further as requirements have become more stringent. Federal procedures are similar to those of California for 1966 models, and were first published in 1966 to be effective with

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*1968 Federal standards were expressed in terms of concentration; 1970 Federal standards are expressed in terms of grams per mile. Both are presented here for ease of comparison.

1968 models.[16] Federal procedures published in 1968 for 1970 models were expanded and amplified.[19]

To obtain Federal certification,[19,24] manufacturers must furnish data showing that the vehicles they intend to offer for sale comply with the Federal standards. They must also provide representative vehicles for confirmatory testing in Federal laboratories. The National Air Pollution Control Administration has its principal motor-vehicle test laboratory in Ypsilanti, Michigan.

To qualify for certificates of conformity, manufacturers must submit applications containing data pertaining to crankcase and exhaust emissions, and, for 1971 models, evaporative emissions. Data supplied must cover both phases of a two-part test program. The first phase of testing provides data that indicate the performance of the emission control equipment after the engine has been broken in, but before substantial mileage has been accumulated. These data are obtained, as nearly as possible, during the first 4,000 miles of operation, using one fleet of cars. The second phase of the test program, using a second fleet of cars, provides data on the durability of the emission control systems.

To complete the requirements of the first phase of the test program, four prototype vehicles are generally selected from each engine class in accordance with representativeness of annual sales. The four vehicles, each powered by the same size engine, are usually selected from the most popular models. These four vehicles make up one segment of the 4,000-mile emission-data fleet. The remainder of the 4,000-mile emission-data fleet consists of similarly selected vehicles (in sets of four) for each engine displacement to be produced. Test results for each vehicle of the emission-data fleet are submitted with the application for certification to Federal automotive engineers for evaluation. These data and confirmatory test data subsequently obtained by testing these vehicles in the Federal laboratory in Michigan are used to determine the representative low-mileage emission level for each engine displacement.

The second phase of required testing provides durability data indicative of performance of control systems or devices over extended mileage. Durability testing is conducted on a second fleet of automobiles comprising a minimum of 4 and a maximum of 10 vehicles under procedures for 1968-69 models, and 12 vehicles under procedures for 1970 models. Each is operated for 50,000 miles under actual driving conditions. During this period of mileage accumulation, emission measurements are made every 4,000 miles in the manufacturer's laboratory. For vehicles equipped with evaporative control systems, evaporative emissions are measured through not less than 12,000 miles for 1970 models, and not less than 50,000 miles for subsequent models. The data thus obtained provide a basis for evaluation of probable emissions over the life of a typical vehicle (defined as 100,000 miles).

Compliance with the Federal standards is ascertained for each class of engine by averaging the 4,000-mile emission data for each engine displacement and adjusting these data on the basis of data from the durability fleet to lifetime emissions for 100,000 miles. The resultant figures are then compared with the standards. If the engine class meets the standards, a certificate of conformity is issued for each model powered by that engine. By law, all vehicles or engines sold that are "in all material respects substantially the same construction as the test vehicles or engines for which a certificate of conformity has been issued . . . (are) . . . deemed to be in conformity with the regulations . . . ."

Federal regulations specify emission measurement equipment and techniques, and compliance with Federal standards is based on the results obtained in accordance with those specifications. For crankcase emissions, the regulations provide only that the manufacturer shall test the vehicle in accordance with good engineering practice to ascertain that the vehicle, equipped and maintained in accordance with the manufacturer's recommendations, can be expected to meet requirements

Table 3-3. LIGHT-DUTY VEHICLE^a EMISSIONS^{24}

	Uncontrolled vehicles, pre-1968			National standards, 1968			
	1963^{b,c} model year car, grams/ vehicle mile–dynamometer cycle	1963^{c,d} model year car, grams/vehicle mile–on the road	Estimated^{d,e} emissions pounds/car/ year–on the road	1968^{b,c} model year car, grams/ vehicle mile–dynamometer cycle	1968^{c,d} model year car, grams/vehicle mile–on the road	Estimated^{d,e} emissions pounds/car/ year–on the road	Percent reduction for 1968 model–year car–on the road
Exhaust:							
Hydrocarbons	10.20	8.87	270	3.43	2.98	90.0	67.0
Carbon monoxide	76.89	44.47	1,370	35.10	20.30	630.0	54.0
Oxides of nitrogen (as NO_2)	5.38	5.26	160	6.76	6.60	200.0	-26^g
Crankcase blowby:							
Hydrocarbons	3.15^f	3.15^f	100^f	0.0	0.0	0.0	100.0
Evaporation:							
Hydrocarbons	2.77	2.77	80	2.77	2.77	80.0	0.0
Total:							
Hydrocarbons	16.12^f	14.79^f	450^f	6.20	5.75	170.0	62.0
Carbon monoxide	76.89	44.47	1,370	35.10	20.30	630.0	54.0
Oxides of nitrogen	5.38	5.26	160	6.76	6.60	200.0	-26.0^g
Oxides of nitrogen (as NO_2)							

Table 3-3(continued). LIGHT-DUTY VEHICLE[a] EMISSIONS[24]

	National standards, 1970				National standards, 1971			
	1970[b,c] model year car, grams/vehicle mile–dynamometer cycle	1970[c,d] model year car, grams/vehicle mile–on the road	Estimated[d,e] emissions pounds/car/year–on the road	Percent reduction for 1970 model year car–on the road	1971[b,c] model year car, grams/vehicle mile–dynamometer cycle	1971[c,d] model year car, grams/vehicle mile–on the road	Estimated[d,e] emissions pounds/car/year–on the road	Percent reduction for 1971 model year car–on the road
Exhaust:								
Hydrocarbons	2.20	1.91	60	78	2.20	1.91	60.00	78
Carbon monoxide	23.00	13.30	410	70	23.00	13.30	410.00	70
Oxides of nitrogen (as NO_2)	6.76	6.60	200	-26[g]	6.76	6.60	200.00	-26[g]
Crankcase blowby:								
Hydrocarbons	0.00	0.00	0	100	0.00	0.00	0.00	100
Evaporation:								
Hydrocarbons	2.77	2.77	80	0	0.49	0.49	15.00	81[h]
Total:								
Hydrocarbons	4.97	4.67	140	69	2.69	2.40	75.00	83
Carbon monoxide	23.00	13.30	410	70	23.00	13.30	410.00	70
Oxides of nitrogen (as NO_2)	6.76	6.60	200	-26[g]	6.76	6.60	200.00	-26[g]

[a] Vehicles with a gross vehicle weight of 6,000 pounds or less.

[b] Tested according to Federal LDV test procedures.

[g] At 2,000 miles (odometer reading).

[d] Assumes 50 percent urban and 50 percent rural driving for the vehicle.

[e] Average first year emission rates.

[f] Applies only to pre-1963 cars.

[g] Estimates range from -15 percent to -50 percent reduction (or a 15 to 50 percent increase).

[h] Recent test data indicate that this is over 90 percent.

for not less than 1 year. Exhaust and evaporative emissions are measured during prescribed sequences of vehicle operating conditions. Exhaust emissions are measured through use of nondispersive infrared analyzers while the vehicle is operating on a chassis dynamometer. Evaporative emissions are determined as the weight of fuel collected in an activated-carbon trap connected to possible raw-fuel vapor-emission points of the vehicle fuel system. The test procedure consists of collecting emitted fuel vapor during three modes (1) diurnal breathing, (2) running, and (3) hot soak.

The issue of the Federal Register[19] containing emission standards and certification procedures for 1970 and later model gasoline-powered motor vehicles has been amended[21] to include labeling of each vehicle by the manufacturer stating that it "... conforms to U.S. Department of Health, Education, and Welfare regulations applicable to (appropriate year) model-year new motor vehicles." This provision was effective February 10, 1970, and requires that the label be permanently attached in a readily visible position in the engine compartment so that it cannot be removed without destroying or defacing the label. In addition to the statement of conformity, the label must contain the following information:

1. The label heading: Vehicle Emission Control Information.
2. Full corporate name and trademark of manufacturer.
3. Engine size (in cubic inches).
4. Engine tuneup specifications and adjustments, as recommended by the manufacturer, including recommended idle speed, ignition timing, and air-fuel mixture setting and/or idle carbon monoxide setting. These specifications should indicate the proper transmission position during tuneups and what accessories (e.g., air-conditioner), if any, should be in operation.

3.3 EFFECT ON EMISSION REDUCTIONS

3.3.1 New Vehicles

Table 3-3 presents vehicle emission data based on the national standards effective with 1968 and later models, and includes emission data for an uncontrolled vehicle for comparison as a base. Data are applicable to new cars (during only their first year of use for those with exhaust emission controls), and are estimated in terms of:

1. Typical emissions, grams per vehicle mile, both on the composite dynamometer cycle and actual on-the-road emissions.
2. Estimated emissions, pounds per car per year, for HC, CO, and NO_X by source, including an allowance for deterioration of control system effectiveness during the first year. Mileage for the first year is assumed to be 13,200 miles.[24]
3. Percent reduction in emissions referred to the uncontrolled car, according to controls in effect as of the date of particular standard.

Table 3-3 does not attempt to indicate the extent of total emissions nationally, which is influenced by the continual entrance of new cars into the vehicle population and by attrition of older cars.

3.3.2 Durability and Surveillance

Data on the effectiveness of emission control systems are obtained during a 50,000-mile "lifetime" of driving over a prescribed course at speeds and under driving modes intended to simulate urban driving. The procedure does not stipulate whether mileage may be accumulated continuously by the manufacturer, but time requirements would almost dictate continuous driving for at least considerable portions of the mileage. Results obtained through this procedure and corresponding use of emission measurements may not truly indicate the effectiveness of a device or system after 50,000 miles have been accumulated on a vehicle, nor be indicative of performance of a device or system in public use.

To investigate the durability and continued effectiveness of emission controls, the Federal Government laboratory at Ypsilanti obtains data from a fleet of vehicles in daily use by its staff, and from vehicles operated by auto rental agencies. The auto manufacturers are calling in individually owned cars in public use for continuing surveillance, and California has a program for measuing emissions of hydrocarbon and CO from 1966 and later model vehicles in public use.[26] Figures 3-1 and 3-2 represent data obtained in

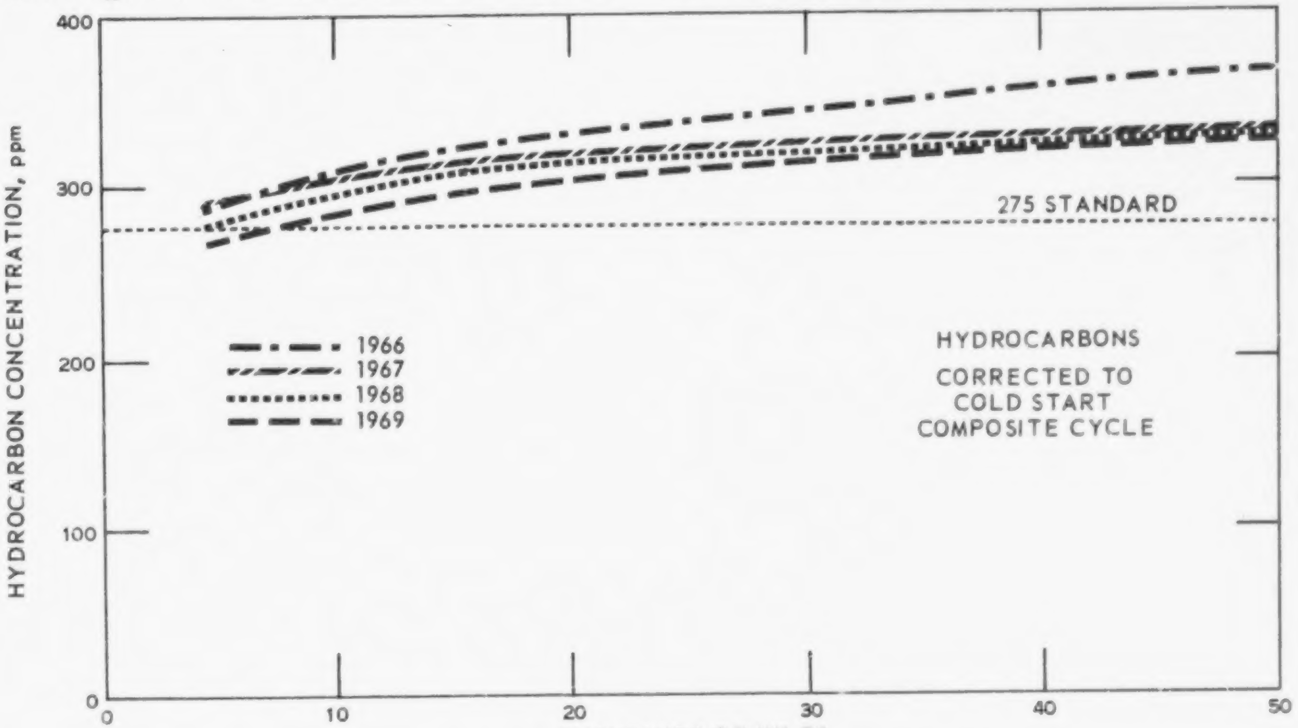

Figure 3-1. Hydrocarbon exhaust emissions versus mileage.[26]

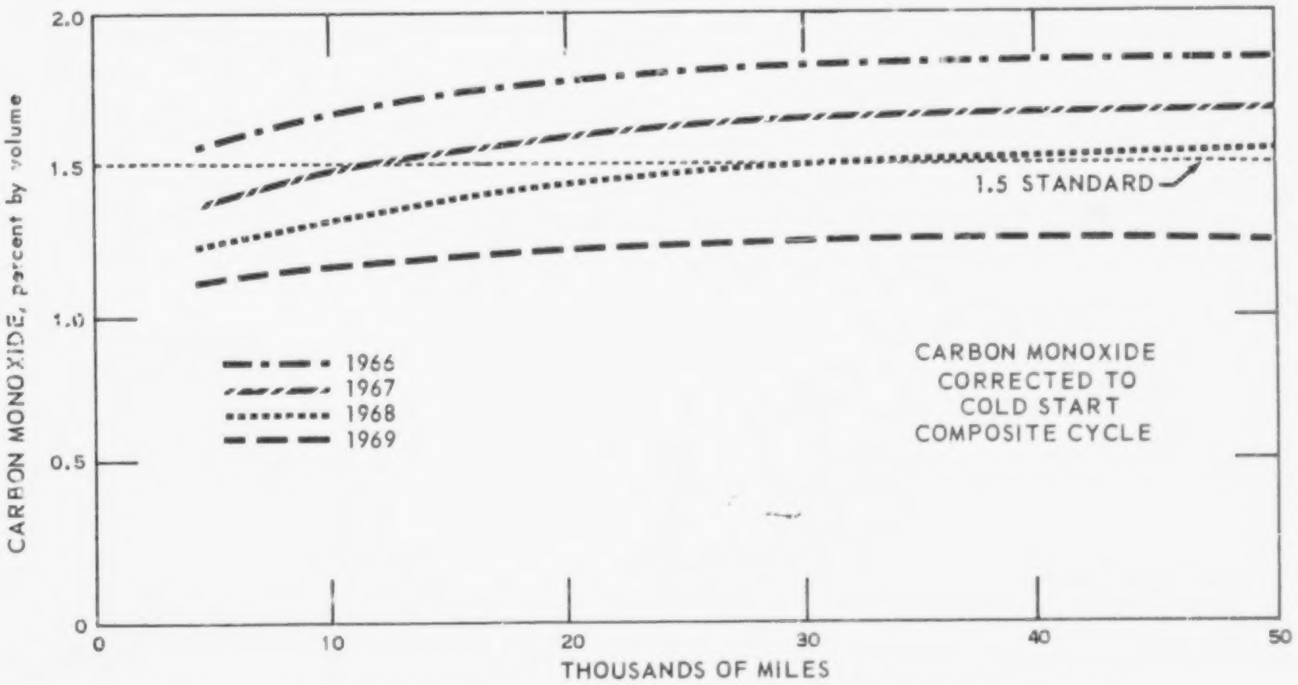

Figure 3-2. Carbon monoxide exhaust emissions versus mileage.[26]

this program. For both HC and CO, the data indicate a gradual decrease in effectiveness to 50,000 miles, which is possibly a plateau of effectiveness. These figures are based on 4,921 tests on California vehicles and are weighted as vehicle types and makes are actually distributed. It should be noted that not many high-mileage, late-model cars are available yet; thus, curves for 1968 and, especially, 1969 models may change as more data become available.

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4. STATE EMISSION CONTROL OPTIONS

4.1 INTRODUCTION

As discussed previously in this document, Federal legislation empowered the Secretary of Health, Education, and Welfare to establish standards for the control of automobile exhaust emissions from new gasoline-powered motor vehicles and engines offered for sale in interstate commerce, beginning with the 1968 model year. The Federal law also specified penalties that can be imposed on anyone who removes or inactivates an exhaust control system prior to delivery of a new vehicle to the purchaser.

At this point, however, Federal authority ends. Any actions to control existing air pollution or prevent future air pollution from mobile sources are left to the individual states under current legislation. There is, therefore, a need for appropriate state action to augment the Federal program if air quality in a region indicates that such measures are, or will be necessary. This section discusses and identifies various optional plans for consideration by the states. Methods of inspection and/or maintenance are effective in reducing emissions of CO and HC from vehicles both equipped and unequipped with emission control systems. Indirect methods of control presented in this section may substantially reduce emissions from the entire vehicle population in an area. Fuel modification, a state option, is considered in Section 6, Fuel Modification and Substitution.

To be fully effective, a state program must minimize emissions from all vehicles or make it possible to identify individual vehicles that are emitting greater amounts of contaminants than originally certified as acceptable, and provide a mechanism whereby these emissions can be reduced. Such high emissions from a population or an individual vehicle may occur for any of several reasons, some of which are discussed below.

Since present control systems for CO and HC depend, for the most part, on achieving substantially complete combustion in the engine, adjustment of all operating conditions that influence combustion is important. Since these adjustments may change over a period of time, proper maintenance is also very important if emissions are to be kept at a satisfactory level. Tests have shown that minor maladjustments that might not be detected by most drivers can increase exhaust emissions far above design level.[1] Thus, engine adjustment and maintenance are extremely important in limiting exhaust emissions. Table 4-1 shows the effects of several maladjustments on CO and HC emissions.

With modern methods of mass production, some variation is inevitable among engines in the dimensions of critical parts and in their assembly and adjustment. These manufacturing tolerances will inevitably result in different emission rates for different vehicles. Within a large group of vehicles, these variations will most likely be characterized by a normal distribution. Inevitably, a proportion of the total vehicle population will emit greater amounts of contaminants than the average for the entire group, even though all are similar in design and construction (Figures 4-1, 4-2).

A percentage of vehicle owners will deliberately attempt to remove or in some way inactivate the control system. This might be done by someone interested in obtaining high acceleration rates, which, generally, will also increase exhaust emissions.

One approach to controlling vehicular emissions is to attempt to minimize emissions from all vehicles. Another is to identify individual high-emitters for subsequent corrective

Table 4-1. EFFECTS OF MALADJUSTMENT[a] ON CO AND HC EMISSIONS[1]

Maladjustment	Air injection system		Engine modification	
	HC, ppm	CO, %	HC, ppm	CO, %
Intermittent miss	570	1.20	650	1.20
Low idle speed	260	1.25	280	1.20
Rich idle	230	1.80	230	1.80
Plugged PCV	280	1.55	280	1.55
Choke too rich	270	1.35	250	1.80
Advanced spark timing	280	1.20	290	1.20
Air injection belt off	520	3.25	--	--

[a] Composite values of typical emission control car properly adjusted after 4,000 miles are 230 ppm HC and 1.2 percent CO for this study.

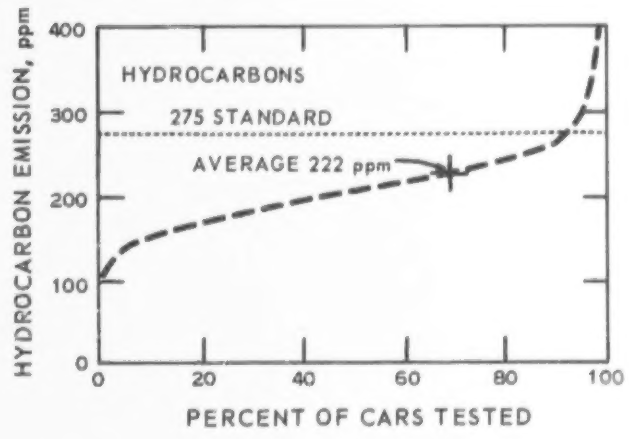

Figure 4-1. Frequency distribution of exhaust HC emission levels as derived from 1655 cold-start dynamometer tests (composite cycle) on 1966 model new cars in California (GM quality audit).[1]

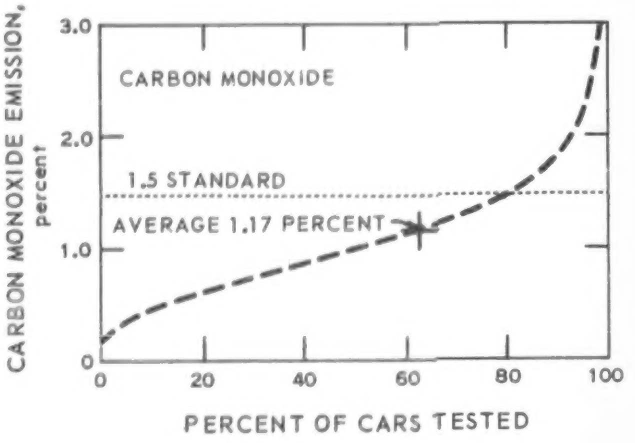

Figure 4-2. Frequency distribution of exhaust CO emission levels as derived from 1655 cold-start dynamometer tests (composite cycle) on 1966 model new cars in California (GM quality audit).[1]

action. The remainder of this section discusses various factors involved in implementing such programs.

4.2 PRESENT STATE PROGRAMS

In considering the problems faced by the states in establishing active control programs, it is helpful to examine some of the efforts that have already been made. A number of states are presently planning or initiating active programs for surveillance, maintenance and/or inspection, and other activities necessary to evaluate the problems that exist and to aid in achieving the necessary degree of control. At present, however, no state is operating a program to ensure continued compliance with Federal emission standards.

California and New Jersey have made major contributions to the knowledge that now exists concerning the methods of control for mobile sources that can be used. Selecting these two states for detailed discussion does not in any way minimize the progress made in other states; the work in these two provides information useful in evaluating the various control options that exist.

4.2.1 California Program

California has taken several steps relating to periodic inspection of vehicles. At the present time, when a vehicle is resold, the new owner (if he is a resident of a county that is in an air pollution control district) must obtain a certificate of compliance from a certified inspection station. This requires that the vehicle be equipped with a crankcase control system.

In addition, the State Highway Patrol is authorized to give tickets for vehicles that emit excessive visible smoke; this provides a partial degree of control by forcing owners of vehicles that are grossly maladjusted or in need of repair to obtain maintenance work.

California uses a random spot-check system for safety inspections; inspection teams move from one location to another and check vehicles without prior warning. In addition to safety checks, these teams also check for the presence of emission control systems on those vehicles required to be so equipped.

Diesel trucks are being checked on an experimental basis for smoke emissions. At a truck weighing station, readings are obtained with a "smokemeter" instrument while the truck is running under heavy load on a dynamometer.

Investigations are in progress to identify other inspection procedures that might be used to advantage. Since past experience indicates that the present control systems are partially effective without inspection of all vehicles, however, a concerted effort is being made to evaluate the cost/benefit aspects of various inspection methods. Since the costs of some types of inspection are considerable, this work should provide valuable information on the incremental reduction of emissions that can be achieved with various inspection methods. The following methods are under study as possible inspection and/or maintenance procedures that might be required:

1. Inspection for the presence of evaporative control devices (starting with 1970 models) and crankcase control devices, plus measurement of exhaust emissions including CO, NO_x, and HC on a complete driving cycle.
2. Exhaust gas measurements at idle conditions only.
3. Tune-up type inspection and maintenance to set engine adjustments to manufacturers' specifications.
4. Checks for the presence of the necessary control system components.
5. A "quick-cycle" dynamometer test and exhaust gas measurement.

4.2.2 New Jersey Program

The State of New Jersey has adopted legislation that, in essence, requires that each motor vehicle manufactured under the Federal emission control standards must pass a test each year to show satisfactory performance of the emission control system and other engine systems. It also requires vehicles manufactured prior to the adoption of Federal standards to pass a test to show that the engine is functioning properly and that emissions are not excessive for a vehicle not equipped with a control system. For controlled vehicles, this will probably have the effect of requiring the vehicle owner to maintain the control system and other engine systems so that they operate according to the manufacturers' specifications on engine adjustment. For uncontrolled vehicles, this will probably have the effect of requiring a tune-up or other maintenance work to eliminate excessive emissions due to gross malfunctions of some vehicles.

To implement this legislation, the State Health Department is developing a rapid test method for use in an annual inspection program, and is now obtaining data to see what emission levels are proper for both uncontrolled and controlled vehicles so that "pass-fail" limits can be established for inspection purposes. Limits are also being set on the emission of smoke from diesel-powered vehicles, and a rapid-test method is being developed to enforce this provision.

Several hundred vehicles have been tested at a State-operated inspection station, using a dynamometer. A simplified four-mode driving cycle is used. Analytical equipment measures unburned HC, CO, and CO_2 in the exhaust. To assist in this work and to provide information potentially useful to all of the states, the National Air Pollution Control Administration has financed a portion of this investigation through a Federal grant. While many problems still remain, this project has achieved a substantial degree of progress in development of an exhaust-measurement type of inspection procedure for mass inspection purposes.

Briefly, the accomplishments to date can be summarized as follows:

1. The simple four-mode test cycle (ACID– for accelerate, cruise, idle, and decelerate) has been developed, and test data indicate that there appears to be some correlation with test results obtained with the longer and more expensive seven-mode test cycle.
2. Different methods of measuring HC have been evaluated. It was concluded that results of analysis with the infrared technique are influenced by fuel composition to some degree and that flame-ionization detectors would be more suitable for New Jersey's purposes. Thus, the present method utilizes flame-ionization detectors to measure HC emissions. Carbon monoxide and CO_2 are measured with infrared detectors.
3. Information has been developed on a semidiagnostic readout, to assist the motorist in securing proper maintenance for vehicles that do not pass the test.
4. Available instruments and data processing methods have been evaluated, and some improvement in the present state of the art has been brought about through the adaptation and use of these instruments.

One factor that has facilitated this work is that New Jersey has State-owned and-operated inspection lanes in which annual safety inspection of all vehicles is performed. Thus, both the experimental program and the later implementation of a complete inspection procedure can be facilitated through closer control than could be achieved in other states in which safety inspections are performed by private garages and service stations. Progress to date indicates that these lanes can be equipped for exhaust measurement at a cost in the range of $15,000 per inspection lane. Included at this price would be a dynamometer, analytical instrumentation, engineering, and installation costs, since the equipment is to be incorporated into existing safety inspection lanes. This is a preliminary estimate subject to confirmation as more experience is gained in such installations. Testing of some 250 cars per day in a single lane appears to be possible. The vehicle would pass or fail this inspection, and diagnostic information could be given to the owner of the vehicle that does not pass. At the present time, data handling is the major bottleneck in processing cars rapidly, but there is some indication that this can be improved through further development.

4.3 LEGISLATION

Several states have already passed legislation that establishes a legal requirement for the control of emissions from motor vehicles. In some cases, this has been by an act of the state legislature; in other cases, official action has been taken by an air pollution control board, commission, or other state agency. Either method is acceptable, depending on the legal requirements of individual states, so long as a firm legal authority is established under which necessary action can be taken.

Most of these laws and regulations include two provisions. The first is a legal requirement that the owner or operator of a motor vehicle should not deliberately remove or inactivate the control system. The second establishes a system of inspection and/or maintenance.

To illustrate, reference is made to a portion of a suggested state air pollution control act drawn up by the Council of State Governments, Committee of State Officials on Suggested State Legislation.[2] Although the exact language may need to be modified to meet legal requirements or special situations in the various states, this law illustrates the provisions that should be incorporated in the legislation. This excerpt is taken from a suggested state air pollution control law which is comprehensive in nature, covering all sources of air pollution, and establishing legal authority and a state agency to conduct a complete program. In this case, the "appropriate state agency" referred to in the draft is similar in nature to the existing air pollution control boards or commissions in many of the states. The "state motor vehicle agency" referred to has, in many states, the legal responsibility for conducting periodic safety inspections of motor vehicles.

"SECTION 16. MOTOR VEHICLE POLLUTION

"(a) As the state of knowledge and technology relating to the control of emissions from motor vehicles may permit or make appropriate, and in furtherance of the purposes of this Act, the (appropriate state agency) may provide by rules and regulations for the control of emissions from motor vehicles. Such rules and regulations may prescribe requirements for the installation and use of equipment designed to reduce or eliminate emissions and for the proper maintenance of such equipment and of vehicles. Any rules or regulations pursuant to this Section shall be consistent with provisions of federal law, if any, relating to control of emissions from the vehicles concerned. The (appropriate state agency) shall not require, as a condition precedent to the initial sale of a vehicle or vehicular equipment, the inspection, certification or other approval of any feature or equipment designed for the control of emissions from motor vehicles, if such feature or equipment has been certified, approved or otherwise authorized pursuant to federal law.

"(b) Except as permitted or authorized by law, no person shall fail to maintain in good working order or remove, dismantle or otherwise cause to be inoperative any equipment or feature constituting an operational element of the air pollution control system or mechanism of a motor vehicle and required by rules or regulations of the (appropriate state agency) to be maintained in or on the vehicle. Any such failure to maintain in good working order or removal, dismantling or causing of inoperability shall subject the owner or operator to suspension or cancellation of the registration for the vehicle by the (state motor vehicle agency). The vehicle shall not thereafter be eligible for registration until all parts and equipment constituting operational elements of the motor vehicle have been restored, replaced or repaired and are in good working order.

"(c) The (appropriate state agency) shall consult with the (state motor vehicle agency) and furnish it with technical information, including testing techniques, standards and instructions for emission control features and equipment.

"(d) When the (appropriate state agency) has issued rules and regulations requiring the maintenance of features or equipment in or on motor vehicles for the purpose of controlling emissions therefrom, no motor vehicle shall be issued an inspection sticker as required pursuant to (cite appropriate section of motor vehicle inspection law), unless all such required features or equipment have been inspected in accordance with the standards, testing techniques and instructions furnished by the (appropriate state agency) pursuant to subsection (b) hereof and has been found to meet those standards."

In addition, a law should establish some sort of legal remedy and penalty to apply in cases of violation. Also, depending on what other legislation may be in existence, definition of the term "motor vehicle" and of other terms used in the act may be necessary. With this type of legislation or regulation, it is possible to establish a legal framework within which an active state program can be conducted.

4.4 OPTIONS ON INSPECTION AND/OR MAINTENANCE PROCEDURES

Many different inspection procedures have been suggested to identify vehicles with unacceptably high exhaust emission rates or to reduce emissions from an entire vehicle population. Several of these are being evaluated at the present time, and it is anticipated that much more information will be available in the near future. This document outlines only the known advantages and limitations of each of these methods so that state agencies can evaluate them and make their own selection.

It is emphasized here that a choice of inspection and/or maintenance methods and other details of an automotive emission control program may properly vary from state to state. Each state agency should evaluate the relative importance of automotive emissions as a present and future source of air pollution in comparison with industrial, municipal, and other sources, and it should establish priorities accordingly for automobile emission control.

Some essentially rural states may attach a lower priority to motor vehicle emissions at this time. Favorable climatological conditions for more rapid dispersion of contaminants may reduce the immediate need for an aggressive program to control vehicular emissions in some localities. Vehicle emission control programs, however, may be needed to maintain acceptable air quality (prevent air pollution) in these states in the future.

In evaluating different inspection and/or maintenance procedures that might be used to prevent and control CO and HC emissions, it is important to point out that the control systems being installed on new vehicles are inherently quite dependable and will achieve a fair degree of reliability, even in the absence of any inspection and/or maintenance procedure. This has been demonstrated in California, where approximately 4 years of experience has been accumulated.

The following inspection and/or maintenance procedures for control of CO and HC exhaust emissions[1,3-12] have been suggested:

1. Visual inspection for the presence of control devices or systems.
2. Requirement of a minor tune-up at some time interval.
3. Requirement of a major tune-up at some time interval.
4. Exhaust measurement at idle to identify high emitters for subsequent corrective action.
5. Exhaust measurement under load on a dynamometer to identify high emitters for corrective action.
6. Exhaust measurement under load on a dynamometer to diagnose reasons for high emissions and to indicate what corrective action should be taken.

Some of the known advantages and limitations of each method are included in the following discussion. Various inspection and/or maintenance procedures have reduced emissions of CO and HC; additional data are needed to demonstrate the cost and cost-effectiveness of such programs in practice.

4.4.1 Visual Inspection

It is difficult to estimate how many vehicles, which were equipped with emission control systems at the factory, have had these systems removed or inactivated. Most studies of deterioration of the effectiveness of control devices have involved cars that the owners have voluntarily made available to the study group. It would seem that owners who volunteer their cars for such a study would not be likely to have disconnected or inactivated the control system. There are indications, however, that a sizeable percentage of motorists do deliberately remove or inactivate their emission control systems.

Legislation, of the type discussed in Section 4.3, coupled with a visual inspection for the presence of emission control systems, could be an effective way to prevent most of this deliberate removal and inactivation. There would be some difficulty in enforcement because some "devices" are engine modifications and adjustments of operating parameters. Alterations of these might be difficult to perceive. A stipulated fine and inspection, on a random spot-check basis or incorporated into a state vehicle-safety inspection program, might be sufficient to stop most deliberate removal and inactivation of control systems; however, such a program would require that inspectors be familiar with at least the types of systems and equipment provided for emission control on the most popular vehicles.

4.4.2 Minor Tune-Up

The minor tune-up type inspection and maintenance program consists of checking adjustments of idle speed, idle air-fuel ratio, spark advance at idle, and possibly other engine operating parameters and resetting them to manufacturers' specifications if necessary. This procedure can usually be accomplished with fairly simple equipment, which is generally available in most garages, service stations, and dealerships. If air-fuel ratio is to be measured directly, some expensive instrumentation will necessarily be involved. A tachometer, which measures engine speed, can often be used to set the idle air-fuel ratio approximately.[3]

Cost and effectiveness of the tune-up type inspection and maintenance program, done on an annual basis, are shown in Table 4-2. Some difficulties associated with this type of program should be pointed out. Mechanics at service stations, independent garages, and even automobile dealerships, in most areas of the country, are not accustomed to tuning cars so as to reduce emissions. Their principal concern is generally to improve performance or operating economy; therefore, it would be desirable for personnel involved in a tune-up type inspection and maintenance program to undergo fairly extensive training. Attempting to train the large number of auto service personnel (with associated high turnover rates) throughout a state would probably be a tremendous undertaking in most cases. The general type of minor tune-up inspection and maintenance described herein is recommended by the Automobile Manufacturers Association.[4]

Although several sources of data [3-7] indicate that emissions of CO and hydrocarbons can be reduced through this type of minor tune-up program, it is likely that oxides of nitrogen emissions would be increased. The effects of minor tune-up on NO_x emissions[3] in one study were:

Number of test vehicles	15
Average emissions of NO_x (as NO_2) as received.	1,777 ppm*
Average emissions of NO_x (as NO_2) after adjustment of idle speed and idle air-fuel ratio	1,890 ppm*
Increase	6.3%

Modification of the basic minor tune-up type of approach to include an oscilloscope diagnosis of the ignition system tends to increase control effectiveness and cost as shown in Table 4-2.

4.4.3 Major Tune-Up

Major tune-up generally includes replacement of spark plugs and breaker points, and possibly other parts of the engine. This is done on the basis of the expected life of these parts, and generally no diagnosis is involved. It may include the adjustments made as part of the minor tune-up program.

The length of time required to perform a major tune-up is such that it is unlikely that a state can provide facilities and personnel at an early date to tune up all registered vehicles on an annual basis. Implementation of a major tune-up program would, therefore, invariably involve the private sector. Since mechanics are generally unaccustomed to tuning cars to reduce emissions, the magnitude of the training program required is again apparent. Since automobile dealerships do only about 25 percent of the total auto service in the country, a training program sponsored by the automobile industry would probably not reach the majority of people performing auto service.

The cost of a tune-up can not be strictly considered as an expenditure only for emission control, because cars are also tuned for

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*Bag-sampling, 10-mode dynamometer cycle, hot-start tests.

Table 4-2. COST AND EFFECTIVENESS FOR SEVERAL TUNE-UP INSPECTION AND/OR MAINTENANCE APPROACHES[3]

Type of inspection and/or maintenance	Reference	Average total annual, out-of-pocket cost per car, including repairs	Immediately after service		Cost-benefit ratios	
			HC reduction (exhaust),%	CO reduction (exhaust), %	$ per car/ % HC removed	$ per car/ % CO removed
Minor tune-up - adjustment of idle speed and air-fuel ratio	3[a]	$3.00	10	16	0.30	0.19
Minor tune-up - adjustment of idle speed and air-fuel ratio, and ignition timing	12[b]	$6.70[c]	18	29	0.37	0.23
Minor tune-up with oscilloscope diagnosis of ignition system	12[b]	$15.00	24	27	0.62	0.55
Major tune-up (approximate figures)	1[d]	$20 - 30.00	10	20	2.00 - 3.00	1.0 - 1.50
Major tune-up by commercial garages - no specific instructions to garages	6[e]	$23.45[f]	5	9	4.69	2.61
Major tune-up by commercial garages - specific instructions written by AMA	6[e]	$29.25[f]	6	8	4.88	3.66
Major tune-up including replacement of air filters and some wiring - idle set 50 rpm over manufacturers' specifications - spark retarded 5 degrees	6[e]	$36.88[f]	27	21	1.37	1.76

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[a] Based on 53% equipped, 47% not equipped with exhaust emission control systems.

[b] Based on 22% equipped, 78% not equipped with exhaust emission control systems.

[c] Reference 12 indicates that this could be reduced to $1.60 per car on a large-scale, full-utilization basis.

[d] All vehicles studied equipped with exhaust control systems.

[e] None equipped with exhaust control systems.

[f] Reference 6 indicates that these costs should be reduced by $8.80 to account for gasoline savings resulting from tune-up, and by $7.81 to account for what owners normally spend voluntarily on major tune-ups. Since all other methods of inspection and/or maintenance have some uncertain dollar value (other than emission control), average, total, annual, out-of-pocket costs are reported for the years in which studies were done.

reasons of performance and economy.[6] Since it is very difficult to assess the benefit derived from a tune-up in terms of dollars saved on gasoline, the value of better performance, or the possible prevention of more expensive maintenance in the future, the costs quoted in Table 4-2 are total out-of-pocket costs for the years in which the studies were conducted.

It is interesting to note the effect climate has on the frequency of tune-up in a given area. Since well-tuned cars start more reliably in very cold weather, motorists in cold climates probably have their cars tuned more often than do owners in warm climates. For this reason, many vehicles in warm climates, which need a tune-up from an emissions point of view, continue to start and perform adequately, and their owners are not induced to have them tuned up.

4.4.4 Exhaust Measurement at Idle

One type of inspection has been proposed in which exhaust emissions at idle are measured, and, thus, vehicles that emit large amounts of CO and hydrocarbons can be identified.[8] Since automobiles are used primarily under conditions other than idle, it may be debated whether a test of emissions at idle adequately reflects emissions during other operating modes. One study has shown that there is some correlation between high emissions at idle and high emissions during other modes of operation.[8]

Any inspection system concerned with measurement of the concentration of CO and hydrocarbons in the exhaust gas involves fairly expensive and sophisticated equipment. Although an idle test may indicate which vehicles have abnormally high emissions, it provides very little diagnostic aid as to what specific type of malfunction or maladjustment produces the high emissions. It should also be pointed out that many engines that are not well tuned may perform adequately at idle, but poorly under load. A measurement of exhaust emissions at idle might not indicate that such an engine needs a tune-up.

4.4.5 Exhaust Measurement Under Load For Purpose of Identifying High Emitters

To measure exhaust under load conditions, an inspection procedure utilizing a dynamometer to simulate driving conditions has been proposed. Emissions as determined on the ACID cycle (Accelerate, Cruise, Idle, and Decelerate) or other load-test cycle would be compared with standards for the maximum allowable emission rates for CO and HC for a given vehicle on the cycle. It would be the owner's responsibility to have his car repaired if it did not pass, and then to return so that it could be retested.

In a large group of vehicles, a few of them could not meet any reasonable emission limit, no matter how much they were repaired or tuned up. This is due to the variability of emissions of both controlled or uncontrolled vehicles. The selection of test standards for this type of program is, therefore, a very difficult task.

Just as there would be some vehicles with very high emissions, there would be some with very low emissions, which might increase because of poor maintenance or maladjustment. As long as the emissions from these vehicles stayed below maximum limits, no corrective action would be taken. There is no question, however, that this type of program identifies vehicles that are high emitters.[9] For this reason, it can reduce emissions of CO and hydrocarbons from vehicles, as shown in Table 4-3.

This system does provide some diagnostic data to assist the owner in obtaining necessary repair work if his car is rejected. Installation cost, for one of the many lanes which would be required for such a program on a statewide basis, is approximately $15,000 per lane, if the dynamometer and exhaust measurement equipment can be incorporated into an existing safety-inspection lane. If, however, facilities were built only to determine vehicle emissions, costs for a building, dynamometer, instrumentation, fire protection system,

Table 4-3. COST AND EFFECTIVENESS FOR SEVERAL TUNE-UP INSPECTION AND MAINTENANCE APPROACHES USING DYNAMOMETERS

Type of inspection and maintenance	Reference	Average total annual, out-of-pocket cost per car, including repairs	Immediately after service		Cost-benefit ratios	
			Exhaust HC reduction, %	Exhaust CO reduction, %	\$ per car/ % HC removed	\$ per car/ % CO removed
New Jersey - ACID identifies high emitters, corrective action taken	12[a]	\$4 - 7.50[b]	13 - 19	7 - 14	0.31 - 0.39	0.57 - 0.54
Clayton - Key Mode diagnosis, corrective action taken	12[a]	\$13.85[b]	24	23	0.58	0.60
ACID type cycle used for diagnosis-indicated adjustments and repairs made	5[c]	\$10.30	6	13	1.72	0.79
Dynamometer and oscilloscope used for diagnosis - indicated adjustments and repairs made - all carburetors rebuilt or replaced - idle set 75 rpm above manufacturers' specifications	6[d]	\$50 - 60.00[e]	28.9	13.4	1.73 - 2.08	3.73 - 4.48

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[a] Based on 22% equipped, 78% not equipped with exhaust control systems.

[b] Estimated - large-scale, full-utilization basis.

[c] All vehicles studied equipped with exhaust control systems.

[d] None equipped with exhaust control systems.

[e] Reference 6 indicates that these costs should be reduced by \$8.80 to account for gasoline savings resulting from tune-up, and by \$7.81 to account for what owners normally spend voluntarily on major tune-ups. Since all other methods of maintenance and/or inspection have some uncertain dollar value (other than emission control) average, total, annual, out-of-pocket costs are reported for the years in which studies were done.

exhaust removal system, and other necessities, would be very much higher.

Since the capital costs of this or any other program involving the use of dynamometers and exhaust measurement instrumentation are quite high, states may find that only a few auto service establishments are willing or able to make the investment required to participate on a franchise basis. It is likely, then, that if a state adopted this or any other program involving such expensive apparatus on a full-scale basis, it would have to be prepared to invest in equipment and training of personnel.

4.4.6 Exhaust Measurement Under Load for Purpose of Diagnosis

The primary aim of this approach is to diagnose all cars in a state so that they can be tuned, if necessary, to reduce emissions of hydrocarbons and CO.

Since there is no absolute maximum emission limit involved, all cars would eventually be able to pass, provided their owners had taken all indicated steps to reduce emissions. Diagnostic data accumulated for all cars would tend to indicate the kind of adjustments or repairs needed to reduce emissions.[10] Cost and effectiveness for this kind of system are shown in Table 4-3. Installation cost for the necessary equipment for one inspection lane, when incorporated in a vehicle safety inspection lane, is about $10,000.[11]

As indicated in Section 4.4.5, costs for independent facilities designed only to determine vehicle emissions would be much higher. Remarks in Section 4.4.5 with regard to capital investment by states are equally applicable to this section.

4.4.7 Crankcase Emission Control Device Inspection

Several options may be considered for crankcase control inspection. One is a crankcase vacuum check with a gage to determine that the control valve on the device is operating properly.[13] This is relatively simple to perform and could be added to an exhaust inspection procedure at little added cost.

Another option is merely to check for the physical presence of the control valve and tubing which constitute a crankcase control device. This will detect deliberate circumvention but will not detect the occasional engine which might be subject to malfunction of the positive crankcase ventilation (PCV) valve. Although malfunction of the valve in a complete, closed positive crankcase ventilation system will not cause emissions of blowby directly, it may cause an increase in exhaust emissions of both CO and HC.[1]

Options for rapidly determining whether the valve is working properly include the following:

1. With the engine running at a high idle speed (1200 to 1500 rpm) and the oil filler cap off, place a sheet of paper or cardboard over the open oil filler pipe and thus check for vacuum in the crankcase. If a vacuum is perceived, the valve is open. If it is stuck open, the engine will idle roughly at low rpm (500 to 700) or will be unable to run at all at low idle speed.
2. With the engine idling at low speed (500 to 700 rpm), clamp and release the crankcase ventilation hose between the PCV valve and the intake manifold. If the valve is working properly, a "click" will be heard each time the hose is clamped and released.
3. With the engine idling at low speed (500 to 700 rpm), and the oil filler cap removed, some traces of visible emissions may vent from the crankcase. If the PCV valve is functioning properly, these emissions will cease and even appear to change direction of flow as the engine speed is increased to a high idle (1200 to 1500 rpm).

The principles of operation of both "open" and "closed" crankcase ventilation systems are discussed in Section 5.1.1. As indicated therein, it is desirable from the standpoints of both emission control and engine life and operation that defective or clogged PCV valves be replaced or repaired.

4.4.8 Evaporative Emissions Control System Inspection

Starting with the 1971 models (1970 models in California), evaporative control devices will be required on new cars by Federal law, and their inspection could be included in any vehicle emission control plan. Two types are described in Section 5.2.1, Evaporative Controls.

Most of these devices are relatively simple in operation, and an inspection to determine that the equipment is on the vehicle would probably suffice. Further information will be available on these devices when they are introduced on more production vehicles, and more detailed information on various inspection and/or maintenance procedures, and on their advantages and limitations may be available at that time.

4.4.9 Oxides of Nitrogen Control System Inspection

No specific guidelines can be established at this time for inspection of systems to reduce emissions of nitrogen oxides, since such systems have not yet been applied to production vehicles. Several are under development and are described in Section 5.2.2, Prospective Control System Development.

4.5 OTHER OPTIONS RELATIVE TO VEHICLE EMISSIONS

In addition to the various controls discussed earlier, other actions can be taken by state and local governments to reduce CO, NO_x, and HC emissions from automobiles. These actions, however, are not directly related to control systems or maintenance procedures. These other measures are additional options that should be considered because they may make an overall state program more effective. One or a combination of the following objectives may be accomplished:

1. A decrease in emission levels of individual vehicles.
2. A decrease in use of individual vehicles.
3. A decrease in number of vehicles.
4. A reduction in traffic congestion to minimize stop-and-go driving and to maintain slow-cruise conditions and thereby affect vehicular emissions.

4.5.1 Substitution of Public Transportation

"Substitution" of public transportation is suggested as a method of reducing the number of automobiles in urban areas. If there is a good transit system, private ownership of automobiles becomes less practical or desirable in some very densely populated cities because of the availability of good public transportation and because of costs and inconveniences incidental to private ownership. Most of the work to investigate and encourage development of public transportation has been focused on expediting movement of masses of people rather, and rightly so, than reduction of vehicle emissions. Generally, however, a result of substitution of public transportation is lower emissions per passenger mile. A determination of the relative merit, from an emission-reduction point of view, of a particular public transportation system is meaningful only when the percent reduction in vehicle-miles traveled caused by the system can be established.

Increase in capacity, reduction of travel time, or combinations of the two are employed to achieve prime objectives in upgrading public transportation. Improvement of bus and rail systems has yielded gratifying results, but route inflexibility remains a problem, solutions for which are being investigated.[14] It should be remembered that the success of a particular public transportation system is related to the population density and the average distance that separates the points between which people wish to travel in the area. Generally, the higher the population density, and the closer the points to be connected, the more applicable is public transportation to a particular area.

4.5.1.1 Bus Systems

Use of bus systems may be expanded by increasing carrying capacity by means of articulated buses or double-deck buses, either of which can reduce operating costs since two-thirds of present costs represent driver wages and fringe benefits.[14] Maximum legal speeds are apparently reached without difficulty by current equipment. A dual mode bus capable of operating on either streets or rails has been investigated experimentally, but requires additional work.[14]

4.5.1.2 Rail Systems

Rail systems include commuter railroads, rapid transit (subways), street cars, and monorails. As a means for conveying passengers, they are concentrated in, around, and between large cities. Their main advantage is their ability to provide rapid transportation for large numbers of passengers.[14] They also have a significant effect on reducing emissions in urban areas. A once-abandoned rail system (the Skokie Swift Project), a demonstration study by the Chicago Transit Authority, for example, reportedly reduced hydrocarbons 13 percent over a 40-square-mile area because of a decrease of 2000 automobile trips per day.[15] Prior to enactment of the Urban Mass Transportation Act of 1964, such rail systems and associated facilities had seen only limited upgrading. From that time through Fiscal year 1969, however, the Act has authorized financial assistance totalling $150 million.[14] The San Francisco BART system is still under construction, but will have a transport capacity of 30,000 seated passengers per hour and a maximum speed of 80 mph.[14]

4.5.2 Road Design and Traffic Control

Traffic routing is a function of right-of-way and roadway planning. Reduction of vehicle emissions may be induced through these aspects of road design primarily as they reduce travel distances and permit sustained moderate speeds.

Table 4-4 shows the effect of vehicle operating mode on emissions of CO, NO_X, and HC, and points out the advantages of traffic flow at low-speed cruise conditions in urban areas.[16] It has also been reported[17] that the logarithms of both CO and HC emissions decrease proportionally as the logarithm of route speed increases. While freeways are not always feasible, the value of the establishment or designation of continuous traffic arteries featuring minimum flow interruption is illustrated. The effectiveness of such arteries in both traffic handling and emission reduction will also benefit from entrances and exits so designed as to avoid traffic bottlenecks and significant variations in mass traffic flow. Clear, direct, and uniform marking of exits and destinations in order to minimize driver indecision at traffic diversion points would also be effective.

Objectives of freeways and other traffic arteries may be furthered by controls conducive to the elimination or reduction of traffic congestion peaks and by abnormal flow interruptions. Staggered working hours have been used where employee concentration is high, largely to facilitate traffic flow. This method is not limited to traffic arteries, but is also generally applicable to metropolitan areas.

Traffic speed may be controlled by automatic sensors and controllers.[18] Optical devices, treadles, or buried loops sense traffic flows and speeds, and modulate mass flow by such devices as traffic lights. Several complex automatic systems are in operation.[14]

Regulations to limit the numbers or use of vehicles may take the form of fuel rationing, limited registration of second or third cars in metropolitan areas, banning or limiting the use of internal combustion engines in affected areas at critical times, and reducing the availability of all-day parking in affected areas. The net effect of some of these measures is the encouragement of car pools.

4.5.3 Control of Older Vehicles

The present Federal regulations for emission control apply to new vehicles as they are manufactured. Because of the normal rate of

Table 4-4. EFFECT OF VEHICLE MODE ON EMISSIONS[16]

Condition		Exhaust				Blowby[a] flow[b]	Fuel system[c] flow[b]-HC	
			Concentration					
Vehicle	Engine	Flow	HC	CO	NO_x		Tank	Carburetor
Idle	Operating	Very low	High	High	Very low	Low	Average to Moderate	Moderate
Cruise								
Low speed		Low	Low	Low	Low	Moderate		Small
High speed		High	Very low	Very low	Moderate	High		Nil
Acceleration								
Moderate		High	Low	Low	High	Moderate		Nil
Heavy		Very high	Moderate	High	Moderate	Very high		Nil
Deceleration		Very low	Very high	High	Very low	Very low		Moderate
Soak	Stopped							
Hot		None	–	–	–	None	High	High
Diurnal		None	–	–	–	None	Moderate	Very low

[a]Concentration of HC is high, CO low, and NO_x very low.
[b]Flows are at least one order of magnitude lower than the exhaust flow.
[c]For a vehicle not equipped with an evaporative emission control system.

obsolescence, however, several years must elapse before most of the entire vehicle population in any metropolitan area will be controlled. This suggests the possibility that present vehicles not equipped with control systems might be controlled to accelerate the rate of progress in the reduction of automotive emissions.

The difficulties involved in such a program are formidable, since it is much more difficult and expensive to install a control system on an existing vehicle than to install a system on a vehicle at the time of manufacture. Since the value of a used car is usually less, the control system will thus cost much more in proportion to the value of the car than for the equipping of a new vehicle.

Exhaust control systems capable of being installed on used cars were tested by the California Motor Vehicle Pollution Control Board in 1963 and 1964, but were never required for used vehicles because of excessive cost. The State of California is still interested in cheaper devices for use on older vehicles, but so far systems have not been certified that cost less than the maximum of $65 established by the legislature to equip a used vehicle.[19] One domestic manufacturer, however, may provide a kit to reduce CO and HC exhaust emissions from pre-1968 cars produced by that company for about $50.[20] This idea was proposed by the automobile industry as early as 1962.[21]

California has been requiring the installation of crankcase control devices on used vehicles since 1964. California requires that such a device be installed (in most cases) when a used car is sold or traded. The difficulties encountered in equipping used cars in California illustrate probable obstacles in attempting this in other jurisdictions.

4.5.4 Long-Range Plans

The states may wish to consider planning for future reductions in vehicular emissions. Some options of this type are listed below.

4.5.4.1 Actions Under Emergency Situations

Planning for emergencies may invite consideration of means to reduce vehicle use. Any locality can expect a few days per year when conditions of the atmosphere will produce a higher degree of air pollution than at other times. Some cities have investigated the possibility of establishing emergency plans for use on such days to limit to the maximum extent possible all sources of air pollution.

Limitation of automobile traffic would decrease the amount of vehicular emissions. There can be difficulties with such a program, however, since transportation by automobile is an integral part of our society in most urban areas, and a reduction in automobile traffic would seriously overload public transportation facilities. Some means of legal enforcement would be required. No state or local governments have instituted a widespread plan in the past, although on some occasions appeals have been made for voluntary cooperation by the public in limiting use of automobiles.

4.5.4.2 Other Vehicle Propulsion Systems

Research efforts have been expended within the past few years to develop other systems of propulsion for vehicular use, including gas turbines, steam engines, electric drives, and others. Some of the most prominent are treated briefly in Section 7, Possible Substitutes for Currently Used Motor Vehicle Engines. A major justification advanced for this effort is the relatively low emissions of some such sources. Realistic evaluation should consider these possibilities over a rather long time interval. At present stages of development, practical systems employing these concepts in mass production are unlikely within less than 10 years. Several more years will be required before vehicles employing these low-emission power sources dominate the vehicle population. Thus, significant reductions of CO, NO_x, and HC emissions by other vehicle propulsion systems are many years away.

4.5.4.3 Certification of Maintenance Personnel

The State of California has established a program of certification for mechanics and inspection stations authorized to grant a certificate of compliance for vehicles at the time of resale. Since proper maintenance of exhaust control systems and other engine systems affecting emissions requires considerable knowledge and skill by a mechanic, a mechanic certification program might aid in reducing maladjustment and malfunction of systems. This suggests the possibility that a state or local certification program might be considered. At the present time, no feasible plan has been found, except in California, where the resale of the vehicle can be used as a mechanism to aid enforcement.

4.5.4.4 Driver Training

Suggestions have been made that some emphasis in driver education on the effects of driving practices upon vehicle emissions may yield benefits.[18] Such an effort might take the form of incorporation in public and private driver instruction programs preparatory to driver license examination, coordination with a vehicle fleet safe-driving instruction program, etc. The effects of driving practices on both concentration and mass of vehicle emissions are recognized in the seven-mode driving cycle specified for Federal certification compliance testing of new vehicles. Accelerations and decelerations, particularly at high rates, result in considerable increase in emissions. No concerted effort in this direction is known, although during wartime periods of gasoline rationing, significant reductions in gasoline consumption per vehicle for commercial fleet operations resulted from concentrated educational and promotional campaigns coordinated with some form of individual merit recognition.

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5. TYPES OF EMISSION CONTROL SYSTEMS

5.1 CURRENT SYSTEMS

Emission control systems presently in use on new cars nationwide include a closed positive crankcase ventilation system, designed to prevent gases that blow by the piston rings from escaping into the atmosphere, and exhaust emission control systems, designed to reduce CO and HC emissions in the exhaust gas.

5.1.1 Positive Crankcase Ventilation Systems

These systems provide the means of circulating air through the crankcase and drawing the circulated air and blowby gases into the intake manifold, where they are carried on to the combustion chambers.

Typically, ventilation air is drawn either directly from the engine compartment (open system), or through the engine air cleaner through a hose (closed system), into a rocker arm compartment, down into the crankcase, across and up into the opposite rocker arm compartment, up through a ventilator valve and hose, and into the intake manifold. Intake manifold vacuum draws gases from the crankcase into the intake manifold.

When airflow through the carburetor is high, additional air from the positive crankcase ventilating system has no noticeable effect on engine operation; but at idle speed, airflow through the carburetor is so low that an excessive amount added by the ventilating system would upset the air-fuel mixture and cause rough idle. For this reason, a flow control valve is used to restrict the ventilating system flow whenever intake manifold vacuum is high. At idle, if abnormally high volumes of blowby gases occur, they are conducted to the air cleaner through the intake air hose in the closed system, or are vented to the engine compartment through the crankcase "breather cap" in the open system, since it does not include a hose from the air cleaner to the crankcase. Figure 5-1 illustrates six- and eight-cylinder engine installations of a typical closed crankcase ventilation system.

After a period of operation, the ventilator valve may become clogged with deposits, reducing and perhaps finally stopping all crankcase ventilation. An engine operated without any crankcase ventilation can be damaged seriously; therefore, manufacturers recommend cleaning or replacing the ventilator valve periodically.

5.1.2 Exhaust Emission Control Systems

The amount of combustibles exhausted from motor vehicles can be reduced by either of two broad approaches, oxidizing CO and unburned HC in the exhaust system or minimizing the mass of these contaminants released from the cylinders.

For the 1966 models sold in California, American Motors, Ford, and General Motors adopted the first approach, injecting additional air into the exhaust ports to further burn the hydrocarbons and CO and, thus, forming additional water and CO_2. Chrysler adopted the approach of establishing engine operating conditions that minimize emission of unburned hydrocarbons and CO from the combustion chambers. Beginning with the 1968 model year, American Motors, Ford, and General Motors adopted the engine modification system for most of their models. For 1969 and later models, the air injection approach is generally used only on vehicles equipped with manual transmissions.

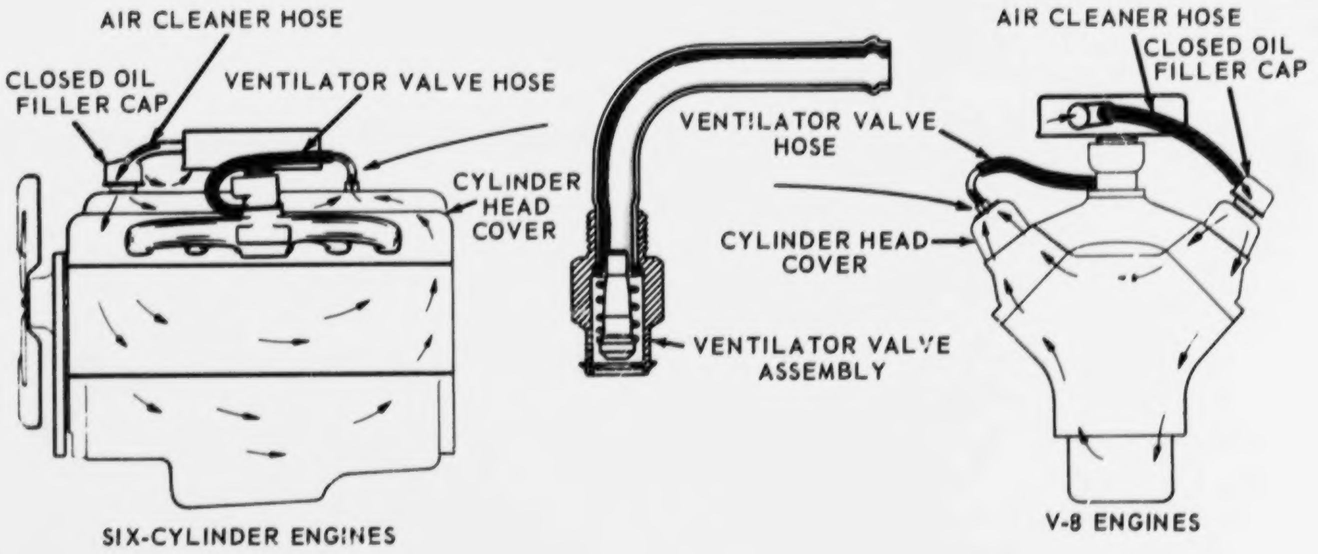


Figure 5-1. Closed positive crankcase ventilation system.[1] (Courtesy of Chrysler Corporation)

The engine modification approach includes designing engines with very good fuel distribution characteristics so that they can operate at quite lean air-fuel ratios. Spark advance characteristics are also tailored for optimum emission control.

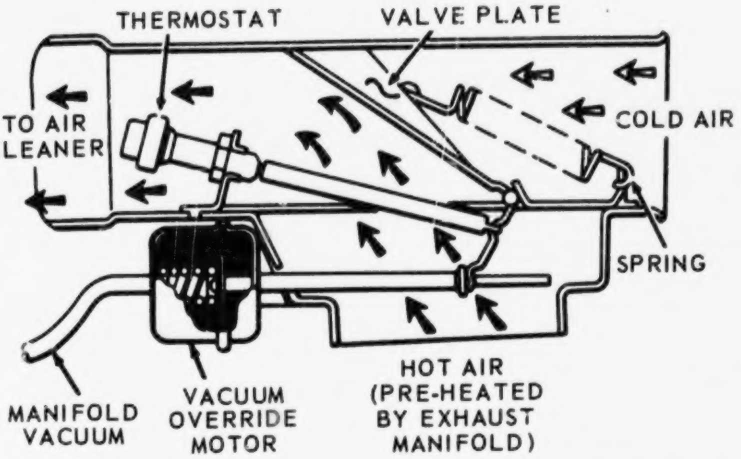
5.1.2.1 Engine Modification Systems

The engine modification approach is used on most of the 1969 model cars produced in the United States. Among the various manufacturers, the approach is known as the Cleaner Air Package (CAP) for Chrysler-produced cars, Improved Combustion (IMCO) system for Ford, Controlled Combustion System (CCS) for General Motors, and "Engine-Mod" for American Motors. Although the systems used by the various manufacturers have a number of features in common, there are some important differences, both among manufacturers and among models within one company.

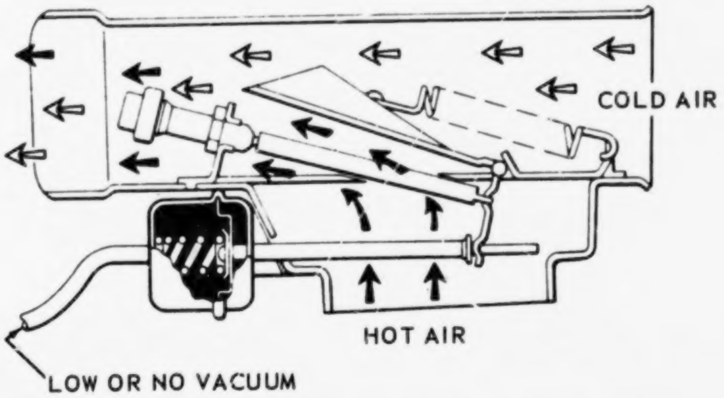
Features shared by essentially all versions of the engine modification system include calibrated carburetors that provide (1) relatively lean air-fuel mixtures for idle and cruise operation and (2) higher engine idle speeds. Refined control of spark timing is also used, and, in some cases, retarded spark timing at idle is employed. In addition, many engines are fitted with special air cleaners and ducting designed to supply heated air at nearly constant temperature to the carburetor. to permit even leaner mixture settings. Most versions also incorporate high-temperature radiator thermostats to raise coolant temperatures and thus improve mixture distribution and promote complete combustion. In some cases, higher-capacity cooling systems are used to handle the additional cooling load at idle that results from wider throttle openings and retarded ignition timing during this operating condition. In addition, combustion chamber design attempts to avoid flame quenching zones where combustion might otherwise be incomplete, and result in high hydrocarbon emissions.

Hydrocarbon and CO emissions are reduced by adjusting the carburetor to a fuel-lean mixture during part throttle and idle operation. "Lean surge" during cruise has been largely overcome through improvement in manifolding (better mixture distribution), better carburetor fuel-metering characteristics, higher coolant temperatures, increased heating of the air-fuel mixture, and, in some cases, provision for heating the incoming air to the carburetor (Figures 5-2 and 5-3).

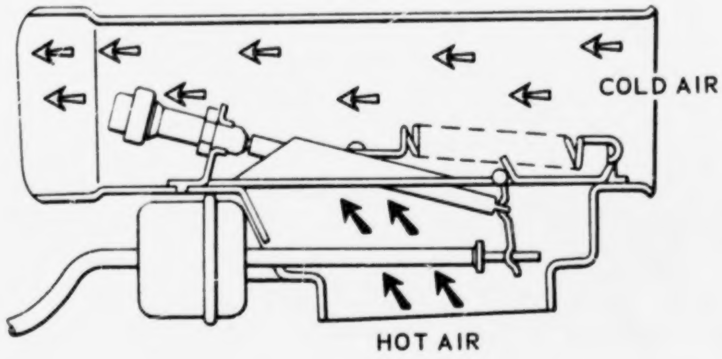
Exhaust emissions of CO and HC are particularly difficult to control during engine idle


THERMOSTAT
VALVE PLATE
TO AIR CLEANER
COLD AIR
SPRING
MANIFOLD VACUUM
VACUUM OVERRIDE MOTOR
HOT AIR (PRE-HEATED BY EXHAUST MANIFOLD)

A. This drawing shows the thermostatically controlled air cleaner with the hot-air plate open. This action takes place during the warm-up period of operation


COLD AIR
HOT AIR
LOW OR NO VACUUM

B. As the engine warms up, the thermostat allows underhood air to enter through the partially opened valve plate. This action occurs during the time that the plate is opened halfway.


COLD AIR
HOT AIR

C. After the engine reaches operating temperature and the underhood air is 105 °F. or higher, the heat valve is closed by the thermostat and only underhood air enters the carburetor air intake.

Figure 5-2. Ford IMCO thermostatically controlled inlet air heater.[2]

(Courtesy of Cowles Book Company)

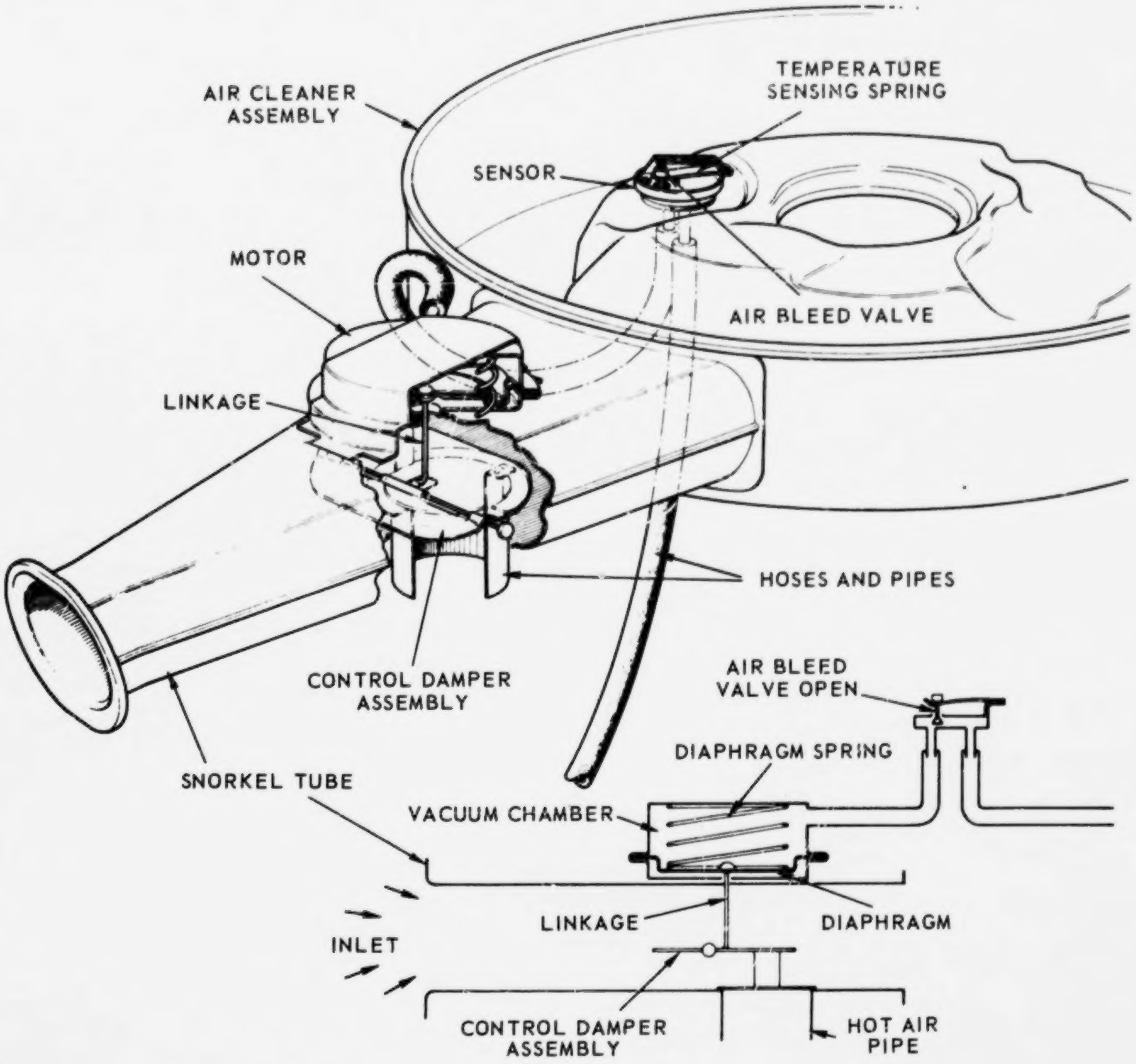
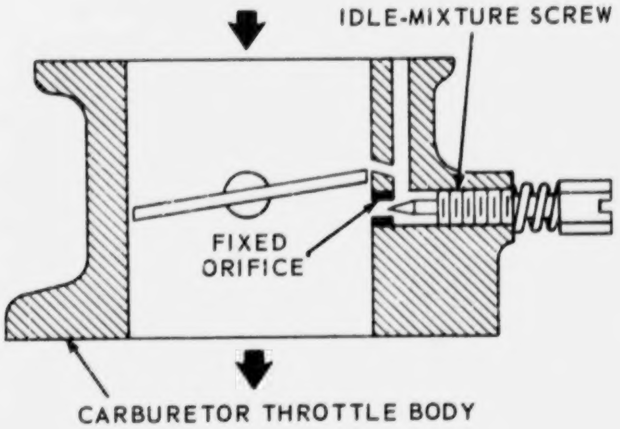
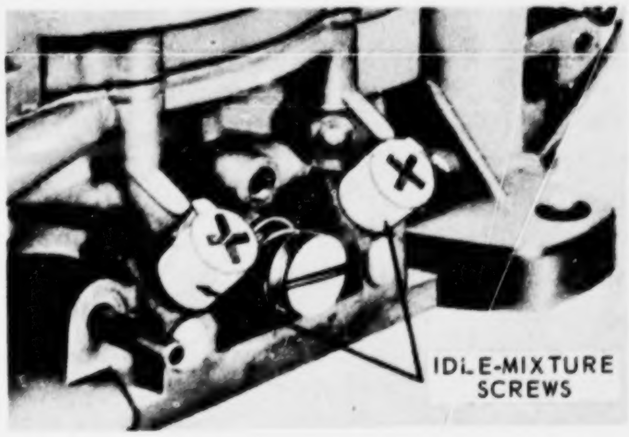

AIR CLEANER ASSEMBLY
TEMPERATURE SENSING SPRING
SENSOR
MOTOR
AIR BLEED VALVE
LINKAGE
HOSES AND PIPES
CONTROL DAMPER ASSEMBLY
AIR BLEED VALVE OPEN
DIAPHRAGM SPRING
SNORKEL TUBE
VACUUM CHAMBER
LINKAGE
DIAPHRAGM
INLET
CONTROL DAMPER ASSEMBLY
HOT AIR PIPE

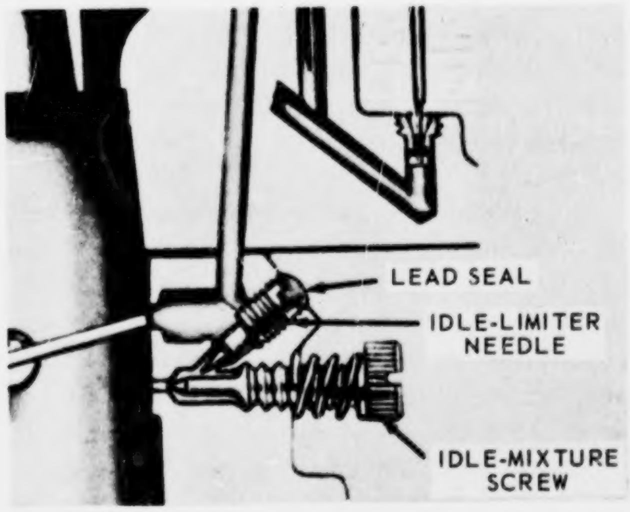
Figure 5-3. Heated air system for General Motors controlled combustion system. Damper is shown with cold air door in open position.3 (Courtesy of Buick Chassis Service Manual)



A. Fixed-orifice control of idle mixture



B. Fixed stops on idle-mixture screws limit rich setting



C. Factory-sealed internal limiter needle with conventional idle-mixture adjustment

Figure 5-4. Typical methods used to limit enrichment of carburetor idle mixture.[4]
(Courtesy of Ethyl Corporation)

and closed-throttle operation (deceleration). Considerable effort has gone into designing carburetor idle systems that will provide a lean air-fuel mixture and minimize emissions during these periods. To ensure that idle air-fuel mixture cannot be adjusted to be too rich (which would tend to increase CO and HC emissions appreciably), some means of limiting idle-mixture adjustment is used on most carburetors. Such devices allow idle mixture to be adjusted leaner than a predetermined value, but not richer. Typical forms of idle-mixture limiters are shown in Figure 5-4. With the fixed-orifice type shown in Figure 5-4A, a conventional idle-mixture screw is used, but maximum mixture richness is controlled by the size of the fixed orifice. Other types of carburetors incorporate fixed stops on the head of the idle-mixture screws to limit the rich setting to a predetermined value (Figure 5-4B). A third type of limiter system (Figure 5-4C) uses a factory adjusted and sealed internal limiter needle in conjunction with a conventional mixture-adjusting screw.

Along with carburetor design changes, altered ignition timing also plays an important part in the reduction of emissions of CO and HC. A number of cars use one or more vacuum-switching control mechanisms to provide refined control of vacuum advance characteristics. Most of these employ some means of retarding the spark timing at idle (and possibly advancing or retarding it during deceleration), while maintaining normal spark advance for acceleration and cruising.

Retarding ignition timing at idle tends to reduce exhaust emissions in two ways. With retarded timing, exhaust gas temperatures are higher, thereby promoting additional burning of the hydrocarbons in the exhaust manifold. More importantly, retarded timing requires a slightly larger throttle opening (increased fuel and airflow) to obtain the desired idle speed. The larger throttle opening not only results in better charge mixing and combustion at idle, but also reduces emission concentrations appreciably during closed-throttle deceleration, as a result of better charge mixing and higher charge density. To further increase the benefits of larger throttle openings, somewhat higher than normal idle speeds are specified for most engines using the engine modification approach to emission control. The use of this technique is restricted since lower concentrations are accompanied by higher exhaust volume flow rates.

Techniques used to retard timing for optimum emission control vary from manufacturer to manufacturer and even between certain engine-transmission combinations. In one of the simpler configurations, a "ported" vacuum source (Figure 5-5) is used with a distributor having conventional vacuum and centrifugal advance mechanisms. Since the vacuum source is above the throttle plate when the throttle is closed, no vacuum advance occurs during idle or closed-throttle deceleration, and basic spark setting plus centrifugal advance controls timing under these conditions.

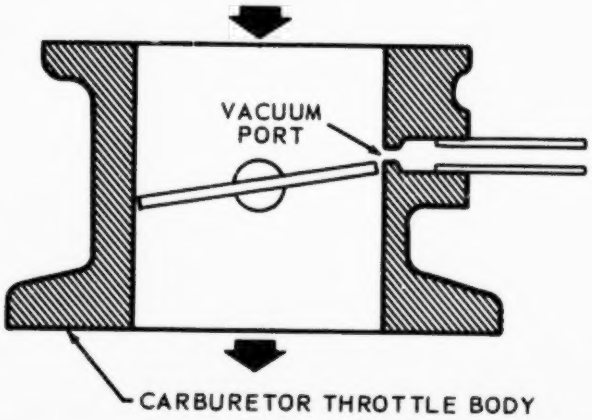


Figure 5-5. "Ported" vacuum source with throttle closed.[4]
(Courtesy of Ethyl Corporation)

With some engine-transmission combinations, driveability and emission control are optimized by spark retarding at idle, and full vacuum advance (instead of retard) during the early part of a deceleration. To attain the desired distributor action in such cases, two alternate vacuum sources–a carburetor port and a manifold port–are used, with the appropriate source selected by means of a vacuum-switching control valve (Figure 5-6) inserted between the sources and the distributor advance mechanism. During all types of operation, except deceleration, the carburetor port controls vacuum advance as before. During deceleration, however, the carburetor port is closed by the throttle plate and the control valve switches temporarily to the manifold port, thereby providing full vacuum advance until manifold vacuum decreases to a level close to idle vacuum. At this point, the control valve switches back and the carburetor port again takes over providing either no vacuum advance (if the throttle remains closed) or normal vacuum advance (if the throttle is opened for cruising or acceleration).

With the two vacuum control systems just described, maximum ignition retard is limited by the basic timing setting of the engine. Engines using these systems frequently have basic settings retarded from those usually considered normal for standard engines–sometimes as much as 5 degrees ATC (after top center). Centrifugal advance curves are then usually tailored with a sharp-rise initial advance characteristic to provide close to normal ignition timing in the middle to high speed range. Since proper ignition timing constitutes a vital link in effective emission control, basic timing should not be advanced beyond specifications. To do so will not only increase exhaust emissions, but may also lead to harmful engine knock or knock-induced preignition.

In addition to the spark-advance control devices already described, a number of cars are using a new type of distributor vacuum advance mechanism to retard ignition during closed-throttle operation. With this device, the usual distributor vacuum advance unit is replaced by one incorporating both vacuum "retard" and "advance" action. Two variations of the concept are found: a dual-acting vacuum advance unit and a dual-diaphragm vacuum advance unit.

Both the dual-acting and dual-diaphragm vacuum advance units take care of closed-throttle retard entirely by control of distributor vacuum. Basic ignition timing and

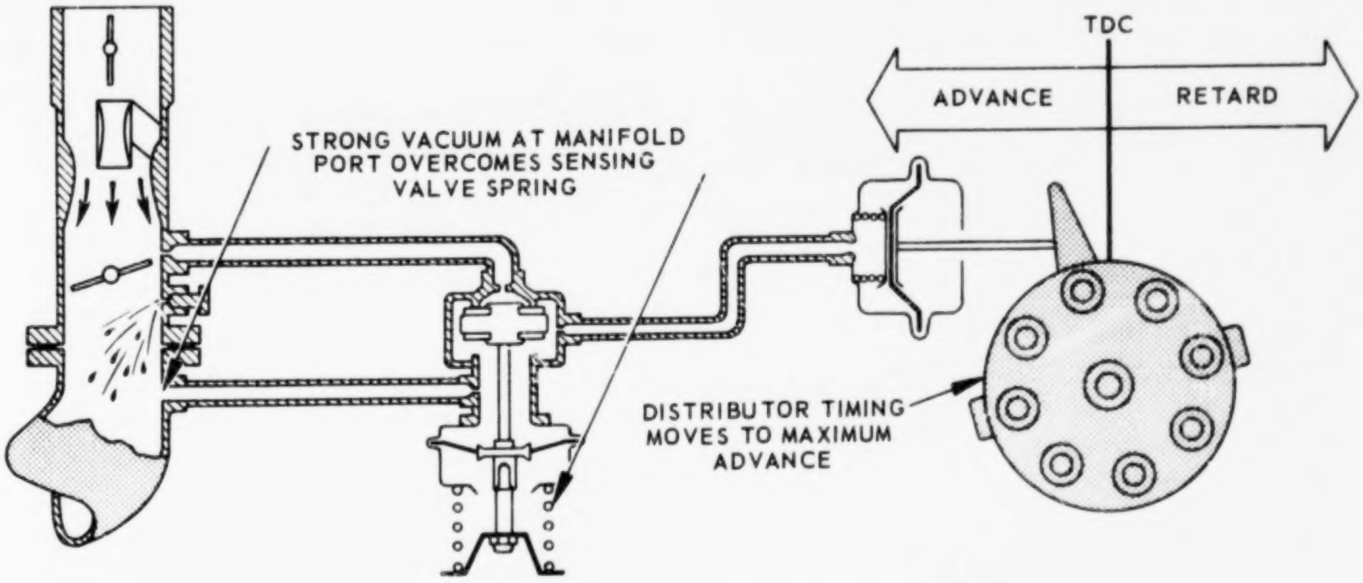

TDC
ADVANCE
RETARD
STRONG VACUUM AT MANIFOLD PORT OVERCOMES SENSING VALVE SPRING
DISTRIBUTOR TIMING MOVES TO MAXIMUM ADVANCE

Figure 5-6. Schematic view showing operation of vacuum switching control valve. Valve is in deceleration position.[2] (Courtesy of Cowles Book Company)

centrifugal advance curves are similar to those for conventional engines. These features allow the engine to be started at near-normal spark advance.

Although cooling systems with the various engine modification control systems are sized to handle the greater heat rejection resulting from retarded ignition timing at idle, some engines may tend to overheat during periods of prolonged idle or in slow-moving traffic. To prevent overheating under these conditions, many engines are equipped with an auxiliary thermovacuum switching valve that automatically provides some timing advance if coolant temperature exceeds a predetermined limit. Such valves have a temperature-sensing element installed in a coolant passage of the engine. When coolant temperatures are normal, the control valve allows the various vacuum retard mechanisms to operate in their normal fashion. If overheating occurs, the valve responds by connecting the vacuum advance mechanism to an alternate vacuum source that temporarily advances idle timing (and hence raises the idle speed) until coolant temperature returns to normal.

5.1.2.2 Air Injection Systems

New cars not employing engine modification use an air injection system to control emissions. Devices of this type are used primarily in cars with standard transmissions and in one make of luxury-type automobile manufactured in the United States. Among the various manufacturers, the air injection system is called "Air Guard" by American Motors, "Thermactor" by Ford, and "Air Injection Reactor (AIR)" by General Motors. Air injection has not been used on Chrysler Corporation cars.

Air injection systems decrease exhaust CO and HC emissions by injecting air at a controlled rate and at low pressure into each exhaust port. Here, the oxygen in the air reacts with the hot exhaust gases, resulting in further combustion of the unburned hydrocarbons and CO that would otherwise be exhausted to the atmosphere. Optimum reduction of emissions by this method depends on proper air injection rates over a wide range of engine operating conditions, carefully tailored air-fuel mixture ratios and spark advance characteristics, and, in some cases, the use of heated carburetor air. Some engines also provide for retarded ignition timing during closed-throttle operation. Basic components of the air injection system are shown in Figure 5-7.

All air injection systems use essentially the same basic air pump, a positive displacement rotary-vane type.

To guard against excessive temperature and back pressure in the exhaust system resulting from high air delivery rates at full throttle and high speeds, a pressure-relief valve is installed in the pump housing. The valve opens to bleed off some of the pump flow at a predetermined pressure setting.

Output from the air pump is directed through hoses and an air distribution manifold (or two manifolds–one for each bank on V-8 engines) to the air injection tubes located in each exhaust port. Figure 5-8 shows a typical tube in an exhaust port. A check valve between the air distribution manifold and the air pump prevents reverse flow of hot exhaust gases in the event that pump output is interrupted.

A vacuum-controlled antibackfire valve is used to prevent flow of air to the exhaust ports during the initial stage of closed-throttle deceleration. The high vacuum that occurs during deceleration causes rapid evaporation of liquid fuel from the intake manifold walls. The resulting rich mixture creates a potentially explosive vapor in the exhaust manifold if injected air is present.

As with engine modification systems, most air injection systems also employ spark retard during idle or idle and deceleration through use of "ported" vacuum sources or dual-diaphragm distributor-vacuum-advance mechanisms.

5.2 PROSPECTIVE EMISSION CONTROL SYSTEMS

5.2.1 Evaporative Controls

Fuel evaporative emission standards applicable to 1971 models (1970 models in California) require that fuel systems be equipped or designed to limit HC evaporative emissions.

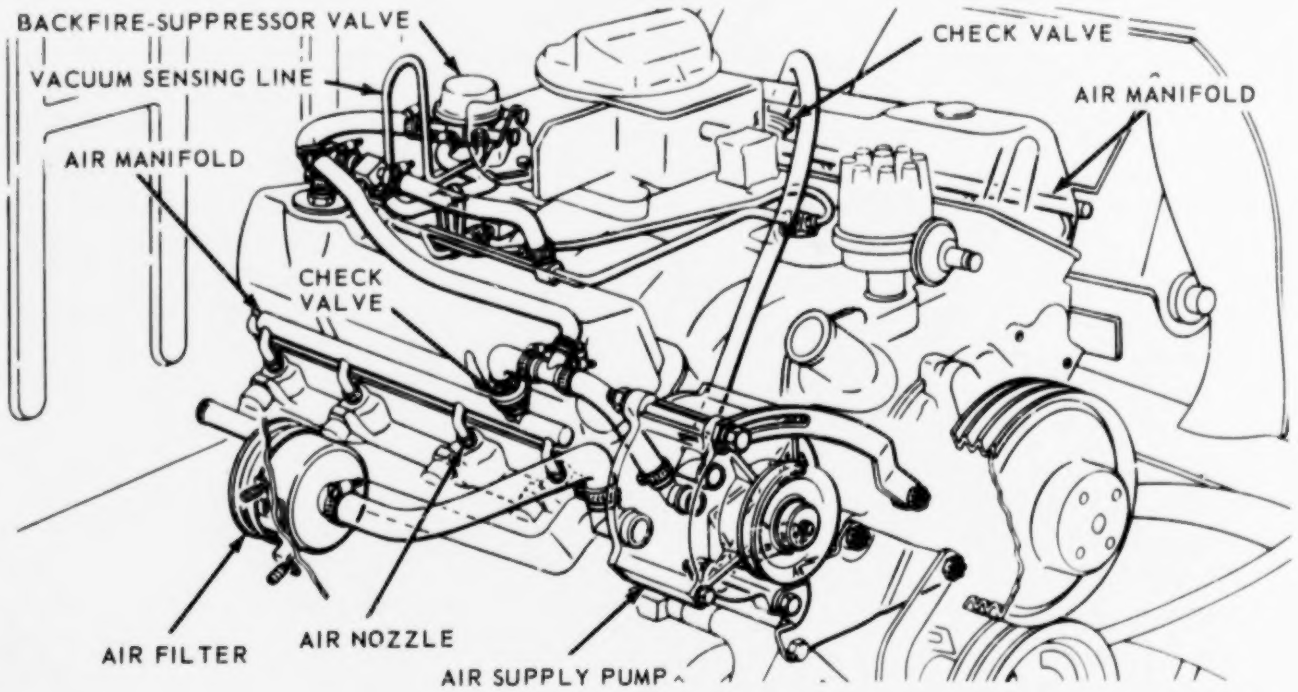


Figure 5-7. V-8 engine with air injection reaction components installed.[2]
(Courtesy of Cowles Book Company)

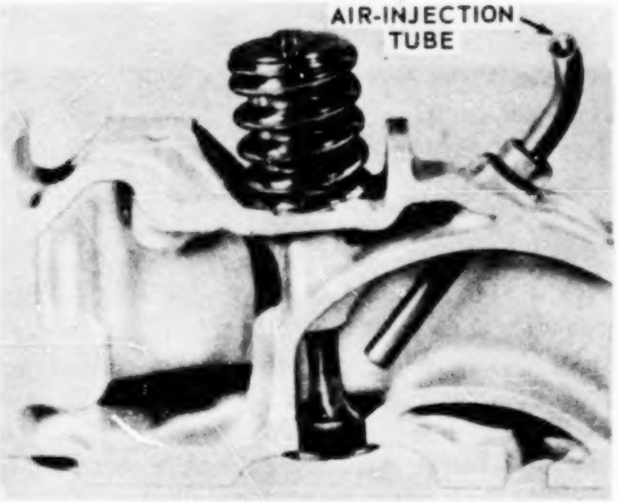


Figure 5-8. Air injection tube in exhaust port.[4] (Courtesy of Ethyl Corporation)

5.2.1.1 General

Gasoline tanks and carburetors are presently vented to the atmosphere. Losses at the carburetor occur almost entirely during the hot soak period after shutting off a hot engine.[5] The residual heat causes the temperature of the fuel bowl to rise to 150° to 200°F, resulting in substantial boiling and vaporization of the fuel. Losses vary because of many factors, but may be as much as 28 grams of fuel per soak period without evaporative controls.

Two evaporative control methods are presently under development. They are the vapor-recovery and the adsorption-regeneration systems. The latter system has been developed to the extent that it was available for one vehicle model[6] introduced at midyear in 1969. Evaporative emissions are a function of fuel vapor pressure and ambient temperature. Current evaporative emission control systems are designed to be used with fuels of 9 pounds or less Reid vapor pressure.

5.2.1.2 Vapor-Recovery System

In the vapor-recovery system, the crankcase is used as a storage volume for vapors from the fuel tank and carburetor. During the hot soak period after engine shutdown, the declining temperature in the crankcase causes a reduction in crankcase pressure sufficient to induct vapors. During this period, vapors emanating from the carburetor are drawn into the crankcase. Vapor formed in the fuel tank is carried to a condenser and liquid-vapor separator; the condensate returns to the fuel tank, and remaining vapors are drawn into the crankcase. When the engine is started, the crankcase is purged of vapors by the action of the positive crankcase ventilation system.

A sealed fuel tank with a fill-limiting device is required to ensure that enough air is present in the tank at all times to allow for thermal expansion of the fuel. A vacuum-relief gas-tank cap is used to admit air to the tank as fuel is used.[7]

5.2.1.3 Adsorption-Regeneration System

In the adsorption-regeneration system, a canister of activated carbon traps the vapors and holds them until such time as they can be fed back into the induction system for burning in the combustion chamber.[7,8] During a hot soak period, vapor from the fuel tank is routed to a condenser and separator, and liquid fuel is returned to the tank. The remaining vapor, along with fuel vapor from the carburetor, is vented through a canister filled with activated carbon, which traps the fuel vapor.

When the engine is started, fresh purge air drawn through the canister strips the activated carbon of the trapped fuel vapor and carries it to the combustion chambers. A purge control valve (if used) allows a flow of air over the hydrocarbon-laden carbon in the canister to strip it of the trapped vapors only at engine speeds above idle. The vapors are then carried to the combustion chamber during periods of engine operation other than idle. The liquid-vapor separator may consist of a small tank mounted high enough to prevent liquid from entering the line to the canister. A float valve, which stops liquid but allows vapor to enter the line, is an alternative design. A sealed fuel tank with air trapping space that cannot be filled with fuel is also required. A vacuum- and pressure-relief gas-tank cap is used with these systems.

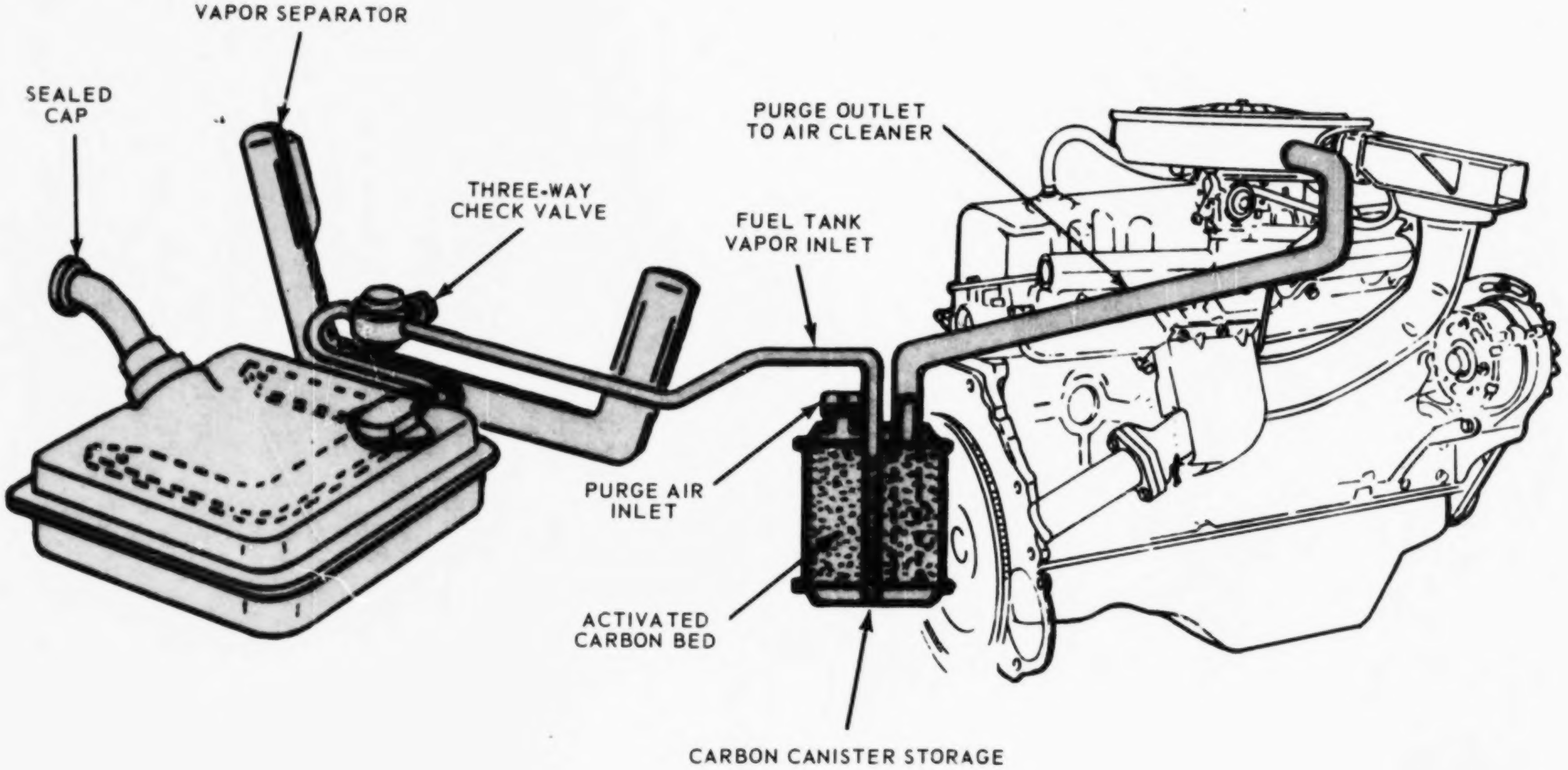

VAPOR SEPARATOR
SEALED CAP
THREE-WAY CHECK VALVE
FUEL TANK VAPOR INLET
PURGE OUTLET TO AIR CLEANER
PURGE AIR INLET
ACTIVATED CARBON BED
CARBON CANISTER STORAGE

Figure 5-9. Adsorption-regeneration evaporative emissions control system.[9]
(Courtesy of Ford Motor Company Engineering Staff)

With some systems a three-way valve is used with a nonventing filler cap to accomplish three major functions:

1. In conjunction with a fill-limiting-type filler pipe, the three-way valve provides a liquid expansion volume in the tank by closing during tank filling, thereby creating a dead air space in the top of the tank. Under pressure, however, the valve opens to permit vapor to pass into the vapor line leading to storage.
2. It vents to the atmosphere to prevent excessive pressure in the fuel tank in the event of an obstruction in the vapor line.
3. It permits air to enter the fuel tank to compensate for consumed fuel or for fuel and air volume loss induced by declining temperatures.

Figure 5-9 shows a typical adsorption-regeneration evaporative emission control system employing a three-way check valve.[9]

5.2.2 Prospective Control System Development–Conventional Vehicles

5.2.2.1 General

Although the states may assume only indirect authority to encourage the use or development of emission control systems, it is well that they have some acquaintance with the types of systems that may be used in the future. A research survey was conducted by the National Air Pollution Control Administration to determine prospective control systems for meeting specified emission-reduction research goals.[10] This survey dealt with research goals for four-stroke and two-stroke spark-ignition engines, diesel engines, and aircraft spark ignition and gas turbine engines.

The opinions of many research experts in the Government and private sector were used to evaluate these approaches and are summarized under the discussion of each type of engine. These experts estimated the research time and cost as well as the probability of achieving the research goals.

Based on these opinions, the study staff evaluated each technical approach for (1) technological feasibility and (2) absolute desirability as a control measure, regardless of feasibility. Technological feasibility takes into account research cost, time, and probability of success. The desirability rating is an ordering of the technical approach alternatives, i.e., number 1 is the best alternative, number 2, second best, etc. The desirability rating takes into account fixed and operating costs to the consumer, the number of emissions controlled, and the increased vehicle maintenance costs.

5.2.2.2 Automobiles and Other Four-Stroke-Cycle, Spark-Ignited Engines

The two programs discussed in this section are: (1) hydrocarbon and CO control in vehicle exhaust and (2) NO_X control in vehicle exhaust. For each program the goals are first listed. The technical approaches to those goals are then discussed, by generic type of control, where applicable. Then opinions of several governmental and private experts[10] regarding the time and cost required to implement these approaches are presented in a table. Finally, evaluations[10] with respect to technical feasibility and order of desirability are presented in another table.

5.2.2.2.1. Hydrocarbon and CO control in vehicle exhaust. The research goals for this program are:

1. First level: Reduce emissions of hydrocarbons to 1.25 g/mile and CO to 17.25 g/mile.
2. Second level: Reduce emissions of hydrocarbons to 0.60 g/mile and CO to 11.50 g/mile.
3. Third level: Reduce emissions of hydrocarbons to 0.25 g/mile and CO to 4.70 g/mile.

Eleven technical approaches initially considered as having potential for control of CO and HC in the exhaust were evaluated as future research and development projects.

Secondary Combustion–Technical approaches:
  Exhaust manifold reactor
  Exhaust manifold reactor with exhaust recirculation

Exhaust system reaction with exhaust recirculation

In the exhaust manifold reactor system a fuel-rich mixture is burned in the engine, and secondary air is added in the exhaust manifold to promote oxidation of HC and CO. The fuel-rich mixture in the combustion chamber inhibits NO_X formation for the reasons stated in Section 2.2.3.1.2. Therefore, exhaust gas recirculation, a control approach for NO_X, may not be needed with the exhaust manifold reactor system.

Technically, the high-temperature exhaust manifold reactor approach offers high potential for HC and CO control. It has good to excellent technical potential for meeting both the first and second level research emission goals. Two types of reactors are being developed to meet the severe temperature problems associated with this control approach: (1) the use of high-temperature-resistant materials and (2) the use of temperature-sensing controllers to limit combustion air or to activate an exhaust gas bypass as a temperature control.

From the design standpoint, the high-temperature-resistant-material approach is thought to be preferable if the materials can be developed at reasonable prices. For both systems a major problem, aside from the high-temperature problem, is the compatibility of the combustor design with the temperature-control technique to be employed.

A somewhat less effective approach to secondary exhaust combustion employs lean engine operation under maximum heat conservation and utilization to promote oxidation in the exhaust system (exhaust system reaction). Such a system has a lower technical probability of success than the manifold reactor system. The low probability of success is due, in part, to the greater complexity of the system and, in part, to the problem areas yet to be resolved. Two basic problems remain unsolved: (1) a carburetion induction system for optimum lean air-fuel operation under all speed and power conditions with the necessary engine timing sensors and controls and (2) the technique and equipment necessary for the maximum conservation and use of engine exhaust heat with adequate durability and economic feasibility. Several advantages result; i.e., the system gives improved fuel economy in contrast to the fuel penalty of the exhaust manifold reactor system. No secondary air supply is required, and material requirements are relatively moderate. On this basis, this technical approach seems to have a good capability of controlling HC and CO to the levels of both the first- and second-level research emission goals.

Engine Factors—Technical approaches:

Lean engine operation
Engine refinement

In lean engine operation the air-fuel ratio is increased through a systems approach in which the carburetor and intake manifold are considered a single operating system. Fuel is pressurized and/or heated to improve atomization. Manifold geometry is also designed to improve distribution.

Overall engine refinement is based on continuing detailed investigations of the effects of engine and fuel parameters on emissions. Basic consideration for control is directed toward lean engine operation under conditions of high heat conservation and utilization. Engine parameters indicating small emission gains will be combined with other control techniques.

Both of the engine factor approaches considered indicate a good capability of meeting the first level of the research emission goals, but a poor capability of reaching the second- and third-level goals. There are theoretical and practical limits on HC and CO reduction by these approaches. Both lean engine operation and engine refinement can control NO_X moderately. These two systems rate the highest in desirability because of their simplicity and the optimum convenience to the user. On this basis, the overall rating is considered to be good.

Catalytic Oxidation–Technical approaches:

Oxidizing catalytic system: unleaded fuels

Dual catalytic system: oxidizing, reducing

Dual catalytic system: reducing agent

Oxidizing catalytic system: leaded fuels

Catalytic oxidation occurs when exhaust gases pass through a bed of active catalyst material. Oxidation of HC and CO starts at some minimum temperature that depends on the catalyst. Rich-mixture exhaust containing CO with a secondary air supply maintains operating temperatures more readily than lean mixture exhaust which contains oxygen but lacks CO. Material requirements or temperature protection considerations are similar to those for exhaust reactors; they are more severe for the rich mixture with the secondary air system.

Generally, the four catalytic oxidation approaches considered for exhaust HC and CO reduction are not now thought to have more than a fair technical potential for success. The principal deterrents to the use of catalytic oxidation as a control approach arise from the lack of a catalyst with a 50,000-mile durability potential under the normal oxidizing temperatures occurring in the exhaust. The technical feasibility of catalytic oxidation as a control approach is higher with non-leaded fuels.

The system desirability factors, considering annual cost, simplicity of technical approach, and convenience, indicate that the overall potential for the development of a satisfactory control approach using a catalytic system can only be considered as fair. It is conceivable that a catalytic converter might be used to further reduce emissions from a well-controlled engine in order to attain the lower research goals. If the engine operated on leaner than stoichiometric air-fuel ratios, secondary air supply would not be required, and material requirements would be less severe.

Ignition and Fuel Control–Technical approaches:

Fuel modifications, additives, or alternative fuels

Ignition system modification

Fuel modification as a control approach has limited potential beyond the first research emissions goal. It has the unique advantage, however, of immediate applicability to both new and used motor vehicles. See Section 6, Fuel Modification and Substitution for a more complete discussion.

The remaining approach, ignition modification, is, in general, considered to have such low technical potential that Government-funded work in this area would not be productive at this time. The potential for improvement through modified ignition systems has been systematically investigated by spark plug and ignition system manufacturers with negative results.

5.2.2.2.2. NO_x control in vehicle exhaust. The research goals of this program are:

1. First level: Reduce emissions of NO_x to 1.35 g/mile
2. Second level: Reduce emissions of NO_x to 0.95 g/mile
3. Third level: Reduce emissions of NO_x to 0.40 g/mile

where NO_x is expressed as NO_2 equivalent. Nine technical approaches initially were considered as having potential for exhaust NO_x control.

Eight of the nine approaches were developed as combined approaches with exhaust HC and CO control. Four demonstrate both high technical feasibility and high system desirability for the control of NO_x, HC, and CO. Significantly, no approach to date, either under consideration or under test, has indicated a technical potential sufficient to reach beyond the first level of the research goals set for NO_x.

Exhaust Gas Recirculation–Technical approaches:

Exhaust recirculation

Exhaust manifold reactor with exhaust recirculation

Exhaust system reaction with exhaust recirculation

Exhaust gas recirculation either as a single approach or combined with a control approach for HC and CO offers the highest potential for NO_x control. The problem of principal concern is the compatibility of exhaust gas recirculation approach with one of the technical control approaches for exhaust HC and CO. Preliminary studies indicate that the exhaust gas recirculation approach has some adverse interaction with many of the secondary combustion approaches used for exhaust HC and CO control. It is considered to be difficult to use with any of the engine modification approaches used for HC and CO control. Despite this limitation, exhaust recirculation is considered, from a technical standpoint, to be the most effective control approach for NO_x.

A secondary problem still requiring a final solution relates to the technique by which the exhaust gas is introduced into the intake system of the vehicle, i.e., the "dirtying" of the carburetor, with its subsequent variation in air-fuel ratio. Another problem lies in exhaust recirculation flow control to meet all power and speed conditions. A combination of technical control approaches using exhaust recirculation with secondary combustion is somewhat lower in technical potential than exhaust recirculation alone. The desirability of a combination system, in terms of simplicity, annual cost, and convenience to the user, can be classed only as good; however, the overall rating of the combined system is considered to have the greatest overall potential for success.

Engine Air-Fuel Ratio Factors–Technical approaches:

Lean engine operation

Exhaust manifold reactor: fuel rich

Two technical approaches employing departures from the normal engine air-fuel ratio operation range are considered as possible NO_x control techniques. Two technical approaches are under development: The first operates at a very lean air-fuel ratio and provides exhaust HC and CO control as well as NO_x control; the second operates at rich air-fuel ratios for NO_x control with an exhaust manifold reactor for control of the HC and CO emissions. Both of these approaches have a good probability of meeting the first level of the research emission goals, but not the more severe levels. In system desirability both approaches rate as the highest of NO_x alternatives because of system simplicity and convenience to the user. On this basis the overall rating of these approaches is considered good.

Catalytic Reduction–Technical approaches:

Dual catalytic systems: oxidizing, reducing

Dual catalytic systems: reducing agents

One dual catalytic system involves the use of a reducing catalyst with relatively fuel-rich engine operation followed by an oxidizing catalyst with secondary air injection. It could be used more effectively with nonleaded fuels.

The other dual catalytic system uses a selective reactant (possibly ammonia) for reducing NO_x under conditions that generally favor the oxidation of CO and HC.

The two reducing catalytic approaches considered for exhaust NO_x control are not thought to have more than a fair to poor technical potential for success. In general, the same basic problems must be resolved for the reducing catalytic approach as for the oxidizing catalytic approaches. In particular, there is a lack of potential catalysts with a 50,000-mile durability under (1) the normal operating temperature occurring in the exhaust and (2) existing fuel lead conditions. Further, the system desirability factors, considering annual cost, simplicity of technical approach, and convenience, indicate that the overall rating of the potential for satisfactory control can at best be considered only fair to poor.

Fuel Modification and Engine Refinement—Technical approaches:

Fuel modifications, additives, or alternative fuels
Engine refinement.

The two remaining approaches considered for NO_X exhaust control, fuel modification and engine refinement, are believed to be of low technical potential. See Section 6.2 for further discussion of the fuel modification approach.

Tables 5-1 and 5-2 summarize the opinions and evaluations of these approaches.

5.2.2.3 Two-Stroke-Cycle, Spark-Ignited Engines

Two-stroke-cycle engines account for a very small percentage of vehicle emissions and therefore have only recently come under consideration for control. The possible control alternatives are more tentative and speculative than automobile controls, since there has been almost no research to support opinions.

Hydrocarbon and CO control is the only program that has been proposed for this type engine. The research goals for this program are:

1. First level: Reduce emissions of hydrocarbon to 1.25 g/mile and CO to 17.25 g/mile.
2. Second level: Reduce emissions of hydrocarbon to 0.60 g/mile and CO to 11.50 g/mile.
3. Third level: Reduce emissions of hydrocarbon to 0.25 g/mile and CO to 4.70 g/mile.

The following information is little more than a description of possible control approaches. Expert opinions on the approaches were sought, but no soundly based opinions could be given. The study team's evaluations of the approaches are presented in a table.

Two-stroke-cycle engines have application where requirements call for simplicity, low cost, and a high horsepower-to-weight ratio. Lubricating oil is mixed with gasoline in ratios varying from 1/16 to 1/50; 1/100 is being considered. The system of loop scavenging, in which the slightly compressed air-fuel mixture flows into the cylinder through an intake port while the exhaust gases exit through exhaust ports on the opposite side, results in some loss of mixture through the exhaust products. This loss, together with relatively rich mixtures required for smooth operation and good response in the two-stroke-cycle engine, results in high HC and CO content in the exhaust gases. Essentially no background is available, and R/D studies have only recently begun to try to determine emissions from

Table 5-1. SUMMARY OF OPINION OF PROPOSED TECHNICAL APPROACHES TO CONTROL EMISSIONS FROM AUTOMOBILES AND OTHER FOUR-STROKE-CYCLE, SPARK-IGNITED ENGINES[10]

Technical approach	Research		Probability of achieving research goal level, %			Annual cost per car, $
	Cost, $ millions	Time, years	1	2	3	
HC and CO control in vehicle exhaust						
Secondary combustion						
1. Exhaust manifold reactor - fuel rich	5-10	2-6	50-100	50-100	0	40-50
2. Exhaust manifold reactor with exhaust recirculation	15	3-6	80-90	80-90	80-90	45
3. Exhaust system reaction with exhaust recirculation	2-4	3-6	30-75	30-75		15

Table 5-1 (continued). SUMMARY OF OPINION OF PROPOSED TECHNICAL APPROACHES TO CONTROL EMISSIONS FROM AUTOMOBILES AND OTHER FOUR-STROKE-CYCLE, SPARK-IGNITED ENGINES[10]

Technical approach	Research		Probability of achieving research goal level, %			Annual cost per car, $
	Cost, $ millions	Time, years	1	2	3	
Engine factors						
4. Lean engine operation	2.5-10	5	50-90	0	0	0
5. Engine refinement	5-30	Continuous	50-80	0	0	5
Catalytic oxidation						
6. Oxidizing catalytic system, nonleaded fuels	3-10	4-5	20-80	20-80	0	40
7. Dual catalytic system: oxidizing, reducing	3-5	5-6	20-75	20-75	0	45
8. Dual catalytic system: reducing agent	5	5	25	25	0	35
9. Oxidizing catalytic system, leaded fuels	2	3	0-90	0-80	0	20
Ignition and fuel control						
10. Fuel modifications, additives or alternate fuels	1.5-3	3-5	10-90	0	0	15
11. Ignition system modification	N/A	N/A	0	0	0	
NO_x control in vehicle exhaust						
Exhaust gas recirculation						
1. Exhaust recirculation	2-5	2-3	0-90	0	0	7.5
2. Exhaust manifold reactor with exhaust recirculation	15	3-6	80-90	0	0	45
3. Exhaust system reaction with exhaust recirculation	3	6	20			15
Engine air-fuel ratio factors						
4. Lean engine operation	2.5	5	50	0	0	0
5. Exhaust manifold reactor – fuel rich	2-12	3-5	0-100	0	0	0-40
Catalytic reduction						
6. Dual catalytic system: reducing, oxidizing (nonleaded fuels)	3-5	6	20-75	20-75	0	40
7. Dual catalytic system: reducing agents	5	5	25	25	0	35
Fuel modification and engine refinement						
8. Fuel modifications, additives, or alternate fuels	No data developed; fuel additives may be possible approach to NO_x control.					
9. Engine refinement	N/A	N/A	0	0	0	5

Table 5-2. EVALUATION OF PROPOSED TECHNICAL APPROACHES TO CONTROL EMISSIONS FROM AUTOMOBILES AND OTHER FOUR-STROKE-CYCLE, SPARK-IGNITED ENGINES[10]

Technical approach	Technical feasibility goal level[a]			Order of desirability[b]
	1	2	3	
Hydrocarbon or CO control in vehicle exhaust				
Secondary combustion				
1. Exhaust manifold reactor, fuel rich	E-G	E-G	F-P	3
2. Exhaust manifold reactor with exhaust recirculation	E-G	E-G	F-P	3
3. Exhaust system reaction with exhaust recirculation	G	G-F	P	3
Engine factors				
4. Lean engine operation	G	P	P	1
5. Engine refinement	G	P	P	1
Catalytic oxidation				
6. Oxidizing catalytic system, nonleaded fuels	G-F	G-F	P	4
7. Dual catalytic system: oxidizing, reducing	G-F	G-F	P	4
8. Dual catalytic system: reducing agent	F	F	P	5
9. Oxidizing catalytic system, leaded fuels	F-P	P	P	3
Ignition and fuel control				
10. Fuel modifications, additives, or alternate fuels	F	P	P	2
11. Ignition system modification	P	P	P	
NO_x control in vehicle exhaust				
Exhaust gas recirculation				
1. Exhaust recirculation	E	P	P	2
2. Exhaust manifold reactor with exhaust recirculation	E-G	P	P	3
3. Exhaust system reaction with exhaust recirculation	G-F	P	P	2
Engine air-fuel ratio factors				
4. Lean engine operation	G-F	P	P	1
5. Exhaust manifold reactor - fuel rich	G	P	P	2
Catalytic reduction				
6. Dual catalytic system: reducing, oxidizing	F-P	F-P	P	4
7. Dual catalytic system: reducing agents	F-P	F-P	P	5
Fuel modification and engine refinement				
8. Fuel modifications, additives, or alternate fuels	No data developed; fuel additives may be possible approach to NO_x control.			
9. Engine refinement	P	P	P	1

[a] E – excellent, G – good, F – fair, P – poor.

[b] 1 – most desirable, 2 – second most desirable, etc.

two-stroke-cycle gasoline engines and possible approaches to their reduction.

Two-stroke-cycle engines used in road vehicles – mostly motorcycles, scooters, and powered minibikes – are subjected to speed and load variations typical of passenger cars. Outboard motors, snowmobiles, and small utility motors (lawn mowers) normally operate about 10 percent of the time at idle and 90 percent at full throttle. These operational differences pose some variation in the application of control approaches.

5.2.2.3.1. Conventional engine redesign. Complete engine redesign with emissions as a major parameter would result in improvement in HC and CO emissions. There was wide difference, however, in forecasting the degree of improvement that could be expected. One approach considered the use of fuel injection, using air alone to scavenge the engine until the exhaust port was closed. This method would also require the use of an engine lubrication system in place of the fuel oil mixtures now used. Although the engine redesign system seems to be the most desirable control alternative if it could be successfully developed, it is obvious that the complexity and cost of the small two-stroke-cycle engine would rise.

5.2.2.3.2. Exhaust reactor with secondary air supply. Experience with manifold reactor development in four-stroke-cycle automotive engines indicates that it should be possible to develop a reactor for oxidizing HC and CO in two-stroke-cycle engine exhaust. The rich mixtures burned would require a supply of secondary air to permit the oxidation process. As is true in the development of exhaust reactors for automobiles, it probably would be necessary to have high-temperature-resistant materials or to have a temperature-sensing control for limiting air or bypassing the exhaust gas. The probability of attaining the first-level research goal appears better for the exhaust reactor than for the conventional engine redesign approach. In complexity and cost the exhaust reactor approach is about as desirable as the engine redesign.

5.2.2.3.3. Advanced engine design Wankel engine. As a backup to fill the requirements of the two-stroke-cycle engine in the event it is not possible to feasibly reduce its emissions, consideration has been given to the use of the Wankel type engine, which has been under intensive development in many countries for several years. The Wankel engine, which operates on the four-stroke-cycle principle, also has a high horsepower-to-weight ratio and is very compact. Experience indicates that its combustion chamber configuration would result in high HC emissions. It is known, however, that this engine can burn lean air-fuel ratios in the exhaust reactor without a secondary air supply. It is estimated that this approach could reach the first-level and possibly the second-level goals and would be a desirable system if the problems associated with the durability of the Wankel engine can be successfully solved.

5.2.2.3.4. Catalytic converter. The same principles that apply to catalytic conversion of exhaust gases in automobile engines would probably also be effective for two-stroke-cycle engine exhaust. Both the need for secondary air supply and the space required for a catalytic converter tend to reduce the desirability of this approach for small two-stroke-cycle engines. The probability of attaining the first-level research goal was rated only fair, possibly because of the unknown effect on the catalyst of oil mixed with the gasoline.

5.2.2.3.5. Fuel studies. Changes in the gasoline-oil ratio should change the composition of the exhaust gas. The technical feasibility of emission reduction by ratio changes for the first-level goal is considered only fair, however.

Table 5-3 presents the highly speculative evaluation of these approaches.

5.2.2.4 Diesel Engines

Diesel engines are used chiefly in trucks, buses, off-road vehicles, and other heavy-duty applications. Because diesel engines generally exhibit fairly complete combustion, their HC and CO emissions are relatively low. One of the principal emissions from diesel engines,

Table 5-3. EVALUATION OF PROPOSED TECHNICAL APPROACHES[10] FOR CO AND HC CONTROL FOR TWO-STROKE-CYCLE, SPARK-IGNITED ENGINES

Technical approach	Technical feasibility goal level[a]			Order of desirability[b]
	1	2	3	
1. Conventional engine redesign	F	P	P	1
2. Exhaust reactor with secondary air	G-F	F-P	P	1
3. Advanced engine design - Wankel engine	G	F	P	2
4. Catalytic converter	F	P	P	3
5. Fuel studies	F	P	P	1

[a] G – good, F – fair, P – poor.

[b] 1 – most desirable, etc.

and one with which this document is concerned, is NO_x. Current emissions range from about 4 to 10 grams NO_x per mile.

The research goals for this program are:

1. First level: Reduce emissions of NO_x to 1.35 g/mile.
2. Second level: Reduce emissions of NO_x to 0.95 g/mile.
3. Third level: Reduce emissions of NO_x to 0.40 g/mile.

Four technical approaches to NO_x control in diesel exhaust have been proposed. These approaches, which are engine and fuel modifications and control techniques, are described below. Opinions of experts in industry and research were sought on the feasibility and desirability of each of the alternatives. These opinions are summarized in a table. The evaluation of the technical approaches, based on the opinions obtained and the knowledge of the study group, are presented in another table.

Technology for the reduction of NO_x emissions in diesel engine exhaust is limited. Since the known need for control is relatively recent, the industry has had little time to carry out engine research and development with NO_x reduction as a design parameter. Few approaches are currently being considered, and half of those being considered are not much past the conception stage. Of the four technical approaches considered, two are under active investigation by engine builders and research laboratories, and only one engine refinement shows both a reasonable probability that the first-level goal will be reached and good desirability for the method of control.

5.2.2.4.1. Engine refinement. Since the enrichment of the air-fuel ratio is not practical in the diesel engine, all other variables of engine operation are being systematically investigated for effect on NO_x reduction and interaction with other engine and emission characteristics. This technical approach appears to be the best method for controlling NO_x emissions with the potential to reach the first- level goal, although it is recognized that compromises may be required. The trade-offs may include derating of engine output and changes in engine variables such as lowering the compression ratio and modifying valve and/or injection timing. These changes may reduce efficiency and increase fuel consumption. At present no agency forecasts even a low probability of achieving the second- or third-level goals.

5.2.2.4.2. Fuel additives. Some researchers believe that prevention of NO_X formation could be a more feasible control approach than dissociating the compound after it has formed. A possible approach would be an inhibitor to NO_X formation that could be introduced into the combustion process through a fuel additive. It is not known how this approach can be carried out, but one leading additive supplier is interested in exploring the possibility. Again, the probability of success appears low, but this approach appears more attractive to some researchers than catalytic converters.

5.2.2.4.3. Catalytic converter. The chemical reduction of NO_X in the exhaust stream appears difficult, if not impossible, because of the oxygen-rich character and the relatively low temperature of diesel exhaust. The use of a CO generator has been proposed as a source for a catalytic converter, but this complication would obviously be undesirable. Catalyst manufacturers, however, are aware of the opportunity of a catalytic approach, and at least one has expressed an interest in studying this approach. Still, the probability of success must be considered low at this time.

5.2.2.4.4. Peak combustion temperature reduction. Reduction of peak combustion temperature by means of induction of an inert material such as exhaust gas or water is an approach that could be effective for NO_X reduction. It is, however, more complex than the derating approach mentioned in the discussion of engine refinements. Injection of inert material amounts to a form of derating, since air normally available for combustion is displaced by nonreactive material.

Tables 5-4 and 5-5 are summaries of the opinions and evaluations of these technical approaches.

5.2.2.5 Aircraft

The basic need for aircraft emission control research and development is to determine the nature and extent of emissions. As further research results in the identification of control needs, the development of appropriate control measures may proceed upon more clearly defined lines.

Specific areas for further investigation are:

1. Emissions for aircraft piston engines and the effects of natural afterburning on emissions.

Table 5-4. SUMMARY OF OPINION OF PROPOSED TECHNICAL APPROACHES TO CONTROL NO_X EMISSIONS FROM DIESEL ENGINES[10]

Technical approach	Research		Probability of achieving research goal level, %			Comments
	Cost, $ millions	Time, years	1	2	3	
Engine and fuel modification						
1. Engine refinement	4	5	60	0	0	Trade-offs involved
2. Fuel additive	1	4	7	0	0	Technology unknown
Control techniques						
3. Catalytic converter	0.5	5	8	0	0	Technology not developed
4. Peak combustion temperature reduction	0.75	4	7	0	0	

Table 5-5. EVALUATION OF PROPOSED TECHNICAL APPROACHES TO CONTROL NO_x EMISSIONS FROM DIESEL ENGINES[10]

Technical approach	Technical feasibility goal level[a]			Order of desirability[b]
	1	2	3	
Engine and fuel modification				
1. Engine refinement	G-F	P	P	1
2. Fuel additive	P	P	P	2
Control techniques				
3. Catalytic converter	P	P	P	3
4. Peak combustion temperature reduction	P	P	P	3

[a] G – good, F – fair, P – poor.

[b] 1 – most desirable, etc.

2. Effectiveness of exhaust gas treatment systems as applied to aircraft piston engines.
3. The relationships between turbine engine emission rates and design parameters.
4. Sampling and analysis techniques for characterizing organic emissions from aircraft turbine engines.
5. Emissions from aircraft during ground operations at major air terminals.

Several technical approaches to the reduction of emissions from aircraft are briefly described.[10]

5.2.2.5.1 Piston engine aircraft. Reduction of CO and hydrocarbon emissions from piston engine aircraft can be accomplished by replacing these aircraft with turbine engine aircraft. This practice is progressing rapidly for the commercial carrier fleet.

Improved carburetors and engine induction systems, accompanied by spark adjustment can be used for operation at lean mixture ratios. Control systems for hydrocarbon and CO emissions may be applied. Auxiliary devices may augment the natural afterburning associated with piston aircraft engines. Systems to reduce CO and HC emissions include the following:

A. Exhaust port air injection.
B. Exhaust manifold reactors.
C. Direct flame afterburners.
D. Catalytic convertors.

5.2.2.5.2 Turbine engine aircraft. More complete fuel combustion and, therefore, reduction of CO and hydrocarbon emissions may be achieved by a reduction of cooling air required to maintain the mechanical integrity of the combustor walls. Use of redesigned fuel spray nozzles to reduce penetration of fuel toward turbine engine combustor walls during idling could reduce air cooling requirements and decrease CO and hydrocarbon emissions.

Reduction of NO_x emissions can be achieved through reduction of maximum temperature in the primary zone of the combustor. Decreased air-fuel ratio may reduce combustor chamber temperature and thereby reduce NO_x emissions.

5.2.2.5.3 Piston and turbine engine aircraft. Emissions of NO_x from piston and turbine engine aircraft, and of CO and hydrocarbons from piston aircraft are reduced in direct proportion to reduction in holding time in the air near airports. Reduction of emissions through reduction of ground operations in the taxi and idle modes is possible. Auxiliary vehicles could tow aircraft to the terminal or transport passengers to aircraft in order to reduce idling time in the waiting line at the takeoff runway.

Since no emission reduction goals have been set, the probability and cost of reaching them are meaningless, and evaluations of technical feasibility and desirability have not been undertaken at this time.

5.3 COSTS OF EMISSION CONTROL SYSTEMS

Table 5-6 shows initial cost ranges from available sticker prices and several industrial sources for systems designed to reduce emissions of CO and HC. They are reported on a nonincremental basis. The cost ranges reported indicate approximately the average total consumer expenditures required per car for the systems listed on a large volume production basis.

The Bureau of Labor Statistics (BLS) of the U.S. Department of Labor has published[11,12] average retail values (which have been used for BLS price index purposes) of exhaust emission control systems for the 1968 and 1970 model new motor vehicles. These are weighted average retail values per car, based on distribution of the various systems used for control of the exhaust emissions. They are based on cost and engineering evaluations of the control systems by the Bureau of Labor Statistics. These estimates of retail values of $16.00 and $21.50 for the 1968 and 1970 exhaust control devices, respectively, are included in footnote b in Table 5-6.

Table 5-6. AVERAGE INITIAL COST RANGES OF EMISSION CONTROL SYSTEMS[a] (NONINCREMENTAL) TO CONSUMER

System	Initial cost
Positive crankcase ventilation system (open)	$ 5-8.00
Positive crankcase ventilation system (closed)	$12-15.00
Air injection exhaust control system	$45-50.00[b]
Engine modification for 1968-69 exhaust control	$18-25.00[b]
Engine modification for 1970 exhaust control	$36-45.00[b]
Evaporative emission control systems for 1971	$36-50.00

[a] Based on available sticker prices and estimates of automobile industry personnel.

[b] U.S. Department of Labor, Bureau of Labor Statistics estimates of the weighted average retail values of exhaust emission control systems as used for price index purposes are (nonincremental):
$16.00 for the 1968 models[11] and
$21.50 for the 1970 models.[12]

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6. FUEL MODIFICATION AND SUBSTITUTION

Sometimes emissions of CO, NO_x, or HC from mobile sources can be changed by altering those characteristics of fuel subject to modification. Fuel characteristics of this type include volatility, hydrocarbon type, and additive content.

Emissions from mobile sources normally originate from:

1. Combustion exhaust gases.
2. Fuel evaporation.
3. Blowby gases (crankcase emissions).

The relative importance of these origins varies among types of mobile sources and depends upon prevailing approaches to emission control being employed. For example, use of certain emission control systems may eliminate, or decrease, the need for fuel modifications aimed at reducing emissions. Generalizations with regard to the influences of fuel modifications on emissions must be qualified. For example, if vehicles are equipped with evaporative emission control systems, reduction in fuel volatility will provide less overall reduction in HC emissions than if vehicles are not equipped with evaporative emission control systems. Some effect, however, is realized immediately with fuel modification. This effect is maximal at the time of initial application and gradually decreases as vehicles with controls replace those without.

6.1 EFFECTS OF FUEL MODIFICATION ON HYDROCARBON EMISSIONS

6.1.1 General

Fuel tanks are a source of evaporative HC emissions. Evaporative emissions occur continuously and increase with increasing temperature. When a gas tank is being filled, the incoming liquid forces the fuel vapor out of the tank and into the atmosphere.

Other nonexhaust HC emissions include carburetor "hot soak" emissions and crankcase emissions. Carburetor emissions may represent light end losses through the air filter or through vents and leaks in the system during hot soak, or may stem from subsequent overrich startup following percolation or slugging of fuel from the carburetor into the intake manifold during hot soak. Crankcase emissions represent composite mixtures of the gases passing the piston rings into the crankcase during various portions of the engine cycle. Consequently, the blowby-gas components range from unaltered fuel through preflame reaction products, to exhaust gas constituents. Lubricant deterioration, resulting from extreme operation, could produce volatile products that would contribute to crankcase emissions.

6.1.2 Gasoline Volatility Reduction

The term "volatility" refers to the tendency of fuel constituents to vaporize and thereby escape from the liquid phase. As such vaporization occurs in a vented system, the resulting fuel vapors simply escape through the vent. In a closed system, however, the vaporized fuel constituents cause the system pressure to increase until no further vaporization occurs. This stable pressure is the vapor pressure of the fuel, and it becomes greater as the system temperature is increased. In the case of complex mixtures of hydrocarbons such as gasoline, the light ends (i.e., the lowest-molecular-weight molecules) have the greatest vaporizing tendency and thereby contribute more to the vapor pressure than do the higher-molecular-weight constituents (higher-boiling-point hydrocarbons). As the fuel is depleted of light constituents (low-boiling-point) by evaporation, the fuel vapor pressure decreases. The measured vapor pressure of gasoline, consequently, depends upon the extent of vaporization during a measurement test. The Reid vapor pressure (RVP) determination is a standardized test in which the final ratio of vapor volume to liquid volume is constant (4:1) so that the extent of vaporization is always the same. Hence, the thus-measured vapor pressure (at 100°F) for various fuels provides meaningful and comparative volatility data.

Fuel modification aimed at reducing the quantity of evaporative emissions is relatively straightforward; it entails adjustment of the fuel composition to reduce volatility. Such changes in fuel composition are not without complications, however. For example, present fuel volatility characteristics are dictated largely by climatic conditions, operating characteristics of current motor vehicles, and economics of fuel manufacture. Excessive reduction in fuel volatility could lead to operating problems such as startup and warmup difficulties. Moreover, significant reduction in fuel volatility in some cases may cause an increase in the quantity of reactivity of exhaust HC.

6.1.2.1 Effects of Volatility Reduction on Performance

The following examples illustrate possible effects of extreme reductions in fuel volatility. Gasoline having a Reid vapor pressure of 10 pounds reportedly gave no startup difficulties in a particular group of automobiles at ambient temperature above 15° F, whereas reduction of Reid vapor pressure to 5 pounds resulted in startup problems at temperatures below 30° F. Also, to prevent warmup stalls or hesitations in these automobiles, the minimum ambient temperature had to be increased from about 60° to 80° F when the Reid vapor pressure was reduced from 10 to 5 pounds.[1] Such extreme reductions in fuel volatility would not normally be considered in most climates. A test of a fuel with substantially reduced volatility was conducted in Los Angeles in 1968 during March and April when the ambient temperature varied through the relatively narrow range of 55° and 70° F. This 1,800-car survey demonstrated that substantial reduction in fuel volatility is acceptable.[2,3]

6.1.2.2 Effects of Volatility Reduction on Emissions

The effects of gasoline volatility reduction on emissions have been studied.[4,5] One study[4] draws the following general conclusions:

1. Total (sum of exhaust and evaporative) HC emissions and reactive HC equivalents (based on the reactivity scale selected for this study) are both reduced by approximately 25 percent by lowering fuel volatility from 9 to 6 pounds RVP when the ambient temperature is 95° F. When the ambient temperature is 70° F, these HC emissions are reduced by 5 to 10 percent.
2. In spite of the overall reduction, exhaust HC emission quantities and reactivity equivalents showed respective increases of 5 to 10 percent and 10 to 12 percent in the range of temperatures considered.
3. Exhaust emissions of CO showed a slight increase with decreasing fuel volatility, but NO_x emissions appeared to be independent of fuel volatility changes in the range considered.

Another investigation,[5] which is applicable only to Los Angeles County because of special conditions of temperature, driving patterns, fuel consumption, and existing fuel composition, to name only a few, resulted in the following conclusions with respect to fuel volatility reduction in Los Angeles County:

1. A reduction in fuel volatility from about 8.5 to 6.0 RVP in Los Angeles County in 1968 would have reduced total organic emissions from gasoline-associated sources about 9 percent. It would also have produced an increase in the quantity of aromatics in emissions associated with gasoline and from all sources; a marked decrease in paraffins in the evaporative emissions and in the total

emissions just cited; a marked decrease in olefins in the evaporative emissions; an increase in the olefins in exhaust emissions; and a modest decrease or no change in the quantity of olefin emissions from other types of emissions or their totals. The overall change in reactivity of HC emissions from all sources that would have resulted from such a change in volatility would be a reduction of about 3 or 0 percent, depending upon the reactivity scale used (based on the reactivity scales selected for this study).

2. In spite of the overall reduction of HC emissions, exhaust HC emissions would have been increased somewhat.
3. Carbon monoxide emissions from motor vehicles would have been increased by about 7 percent.
4. Because the total emissions remaining uncontrolled are expected to decrease rapidly in the years ahead, benefits in terms of both total HC emissions and reactive equivalents prevented from entering the atmosphere would decrease each year until about 1985, starting in 1970, because of installation of evaporative control devices on all new cars sold in California. During this period, an illusory increase in percent reductions in both total HC emissions and reactive equivalents would occur.

6.1.2.3 Costs of Volatility Reduction

A study[6] parallel to the one discussed immediately above[5] was conducted to determine the costs of gasoline modification in Los Angeles County. It, too, is applicable only to Los Angeles County. The reported estimated cost to the producer for reducing RVP from about 9 to 6 pounds would be approximately 1.33 cents per gallon for large refineries and approximately 2.13 cents per gallon for small refineries. Total capital investments needed to achieve this change were estimated at $56 million for the large refineries and $4.2 million for the small refineries.

A similar study[7] reported estimated average costs to the producer, on a nationwide basis, for reducing the percent of gasoline evaporated at 160° F from 30 to 20 percent, and to 10 percent (generally considered as being approximately indicative of reductions in currently used gasoline RVP from 10 to 7.5, and to 5 pounds[4,7]) as 0.7 cents per gallon and 1.6 cents per gallon, respectively. It should be stressed that all these costs are quoted as costs to the producer rather than to the consumer.

Estimated capital investments were also reported in this study.[7] Investments would be approximately $680 million for achieving the 20 percent evaporated at 160° F gasoline and $1.83 billion for the 10 percent evaporated at 160° F on a nationwide basis.

6.1.3 Removal of Highly Reactive Gasoline Constituents

In some cases, alteration of fuel composition to reduce the reactivity of evaporative HC emissions may be more effective than adjustment of fuel volatility. For example, substitution of saturated hydrocarbons for more reactive hydrocarbons, such as volatile olefins, may be employed to reduce the reactivity of the evaporative emissions without affecting fuel volatility.[8,9]

6.1.3.1 Effects of Olefin Removal on Emissions

The effects of removal of olefins from gasoline on emissions have been studied.[4,5] One study[4] draws the following general conclusions:

1. Modifying a gasoline of average volatility by replacing the C_4 and C_5 olefins with corresponding paraffins (and no accompanying change in fuel volatility) has no effect on gross HC emissions, but reduces the reactivity equivalent approximately 30 percent at 95° F and 20 percent at 70° F (based on the reactivity scale selected for this study).
2. Extending the C_4-C_5 olefin replacement to include all olefins boiling below 220° F gives only a small additional reduction in reactivity equivalent (e.g., from 30 to 37 percent at 95° F).

3. The reactivity equivalent of the exhaust HC emissions is unaffected by light-olefin replacement. Thus, the benefit of this fuel modification is reflected only in the evaporative losses.
4. Emissions of CO and NO_x are relatively unaffected by olefin removal.

Another investigation,[5] that is applicable only to Los Angeles County because of special conditions of temperature, driving patterns, fuel consumption, and existing fuel composition to name only a few, resulted in the following conclusions with respect to the removal of olefins from gasolines in Los Angeles County.

1. A change during 1968 from the base fuel to one which had about the same RVP, but in which the C_4 and C_5 olefins had been replaced with comparable saturates, would have produced a reduction of less than 1 percent in the quantity of HC emissions from vehicles. It would also have produced a moderate reduction in olefins emitted from evaporation and in the total emissions of olefins from all sources. There would have been small changes in emissions of paraffins and aromatics from individual types of sources and in their totals. The net effect on the reactivity of HC emissions from all sources would have been a net reduction of about 5 to 6 percent, using either of the two reactivity scales selected for this study. Reactivity of emissions from gasoline-associated sources would have been reduced approximately 6 to 7 percent by either reactivity scale (based on the reactivity scales selected for this study).
2. Exhaust emissions of CO would have been increased approximately 7 percent (per vehicle), but NO_x emissions would not have been affected appreciably.
3. Benefits in terms of total reactive equivalents prevented from entering the atmosphere would decrease each year until about 1985, when essentially all cars will be equipped with evaporative emission controls as well as exhaust and crankcase emission control systems. Percent reductions of reactive equivalents, however, would increase every year until then, but only because the total quantity of HC emissions and reactivity equivalents are expected to decrease rapidly in the years ahead.

Reactivity of fuel constituents should be considered in a discussion of engine exhaust HC emissions. Engine exhaust gases represent the largest source of HC emissions. Their occurrence is due to insufficient combustion air, incomplete mixing of fuel and air prior to combustion, and/or quenching of the air-fuel mixture adjacent to the walls of the combustion chamber. Quenching is well established as the most significant mechanism leading to exhaust HC emissions in properly designed spark-ignition engines.[10]

The presence of a flame-quench zone adjacent to solid surfaces is substantiated by basic combustion theory and many experimental observations.[11] The thickness of the quench zone varies with other combustion parameters such as pressure, gas flow velocity past the surface, turbulence, and air-fuel ratio.

The following is cited to illustrate the significance of the quench zone relative to engine exhaust HC emissions.[12] This information was obtained by sampling the quench zone in a single-cylinder, spark-ignition engine operating on propane-air mixtures. Depending upon operating conditions, the exhaust HC emissions contained from 16 to 98 percent unaltered fuel. The maximum concentrations of this fuel occurred at the quench surface, and the maximum concentrations of fuel hydrocarbon derivatives occurred a short distance from the surface. The composition of these gases continued to change after combustion as the unaltered fuel continued to react in the hot cylinder and exhaust system during blowdown. These results clearly demonstrated that the exhaust HC emissions can be largely explained on the basis of the quench-zone gases.

In view of the foregoing, it is apparent that only those fuel modifications that affect the quench zone and the subsequent reactions of the quench-zone gases should appreciably affect exhaust HC emissions from currently used spark-ignition engines. As in the case of evaporative emissions, not only the quantity of emissions, but the reactivity of the emissions, must be considered. Fuels containing substantial concentrations of highly reactive hydrocarbons have been observed to produce substantial increases in exhaust HC reactivity relative to that of less reactive fuels. In such cases, those fuels containing the largest concentrations of reactive olefins[13,14] produced the most reactive exhaust HC emissions. On the other hand, other experimental data have indicated little or no effect on exhaust HC emission reactivity when olefin and aromatic concentrations were varied through ranges typical of commercial practice.[15] Reductions in exhaust olefins resulting from reductions in fuel olefin reach a limiting value because of "cracking" of paraffins and formation of olefins during combustion.

6.1.3.2 Costs of Olefin Removal

A parallel study[6] to the one concerning gasoline modification in Los Angeles County[5] was conducted to determine the costs of such modification. It, too, is applicable only to Los Angeles County. Reported costs to the producer for removing C_4 and C_5 olefins would be approximately 1.04 cents per gallon for large refineries, and 0.24 cent per gallon for small refineries. The lower cost for small refineries may be due to their ability to use processes for olefin saturation that larger refineries could not use. A similar study[7] reported estimated costs to the producer of 0.25 cent per gallon for C_5 and lighter olefin removal, and 0.7 cent per gallon for C_7 and lighter olefin removal on a nationwide basis. It should be stressed that all these costs are quoted as costs to the producer rather than to the consumer.

Estimated capital investments for the Los Angeles area study[6] were reported to be $66.5 million for the large refineries and $525,000 for the small refineries. Estimated capital investments were reported[7] as approximately $410 million for C_5 and lighter olefin removal, and approximately $1.13 billion for C_7 and lighter olefin removal on a nationwide basis.

6.1.4 Effects of Lead on Emissions

Published data[16-18] indicate that the quantity and/or reactivity of exhaust HC emissions may increase as deposits accumulate in the combustion chamber. Analysis has shown that these deposits consist substantially of lead. It has also been shown that leaded gasoline causes increased difficulty in oxidizing CO and HC in the engine exhaust by the use of a catalyst.[19] For these reasons, some consideration has been given to the use of nonleaded fuels in gasoline engines. A study concerned with the economics of leaded and nonleaded gasoline production[20] reports that the added cost for producing conventional octane-number gasoline without the use of lead alkyl additives would be 2.15 cents per gallon.

6.1.5 Diesel Fuel Modification

With compression-ignition (diesel) engines, the relatively low-volatility fuels do not lead to significant evaporative losses, and the wall-quench zone does not present as serious a problem as it does in conventional spark-ignition engines. This is because of the inherently different fuel delivery systems and ignition characteristics in these two types of engines. A major cause of HC emissions from diesel engines is incomplete combustion of the dispersed fuel droplets, sometimes manifested as white smoke. Although barium-containing fuel additives are known to suppress diesel-engine black smoke (particulate carbon), they do not appreciably influence white smoke emissions.[21]

The only fuel characteristic that is known to be related to diesel white smoke is the cetane number, with smoke decreasing with increasing cetane number. The addition of cetane improvers, such as isopropyl nitrate, exerts a strong white smoke suppression effect, particularly during warmup periods.[22,23] This probably reflects more complete fuel droplet evaporation and combustion because of the reduced ignition delay (reflected by the higher cetane number) in the fuel vapor surrounding each droplet.

6.2 EFFECTS OF FUEL MODIFICATION ON CO AND NO_x EMISSIONS

Fuel modifications to reduce emissions of CO and NO_x would involve changes in fuel characteristics in order to permit combustion to occur under conditions that are not conducive to formation of these substances.

6.2.1 Spark-Ignition Engines

Experimental evidence indicates that a decrease in the volatility of conventional spark-ignition fuels may slightly increase CO exhaust emissions.[4,5] Also, an increased octane number, which will allow spark-timing advance, may lead to increased emissions of NO_x for fuel-lean operating conditions; for stoichiometric and fuel-rich conditions, NO_x emissions may be decreased, particularly at the most advanced spark-timings.[24] Nevertheless, for all practical purposes, it is generally accepted that emissions of CO and NO_x are relatively insensitive to modifications of conventional spark-ignition fuels.[15]

Formation of NO_x during combustion of gasoline fuels can be diminished significantly by water injection into the intake manifold.[25] Although this technique is not fuel modification directly, it is a modification of the composition and temperature of the inducted charge, and appears to be effective in reducing NO_x emissions. The introduction of water vapor into the combustion chamber decreases the maximum cycle temperature because of its dilution effect. Intake-manifold water injection has a further advantage in that its evaporation cools the gases in the induction system. This increased gas density results in higher mass flows through the engine and thereby provides higher maximum power levels. Disadvantages of water injection are the possible formation of sludge in the engine crankcase and the acceleration of engine wear.

6.2.2 Compression-Ignition Engines

It has been shown that reasonable changes in volatility or cetane number do no appreciably influence either CO or NO_x in diesel exhaust.[22,26] Recent experimental evidence, however, indicates that control of combustion temperatures in diesel engines by use of cetane improvers may eventually lead to reductions in NO_x emissions.[23]

6.3 FUEL SUBSTITUTION

Although investigations of chemical modifications of fuel have included the use of ethyl alcohol or ammonia as fuel or fuel additives, no significant developments have resulted from such investigations.[27-30]

The substitution of normally gaseous hydrocarbons for normally liquid gasoline fuels has been investigated extensively. Such substitute fuels are liquefied petroleum gas (LPG), liquefied natural gas (LNG), and compressed natural gas (CNG).

LPG products are mixtures containing primarily propane and butane, with vapor pressures ranging from about 100 to 300 pounds per square inch (psi) at normal ground-level atmospheric temperatures. The utilization of LPG fuel in mobile engines necessitates a pressurized fuel tank and a vaporizer-regulator LP-gas carburetion system. In other respects, the engine and its operation are comparable to gasoline-fueled engines. In fact much of the reported information on LPG engine operation was obtained by running modified conventional spark-ignition engines.

For various combinations of operating conditions with LPG-fueled engines, significant improvements in economy and emission reductions have been reported.[31,32] It has been shown that fuel-lean operations effect significant reductions in HC and CO emissions, but sometimes at the expense of increased emissions of NO_x for near-stoichiometric mixtures.[32] Operation at very fuel-lean (high) air-fuel ratios, however, may tend to reduce combustion temperatures and, therefore, decrease NO_x emissions. On the other hand, operation with fuel-rich air-LPG mixtures, while using a catalytic muffler, produces low emissions of NO_x and HC, with somewhat higher CO concentrations (but lower than 1968 Federal standards).[32]

The predominant hydrocarbon in natural gas used for LNG or CNG applications is methane. This, the lowest-molecular-weight, and hence most volatile, hydrocarbon, boils at -259° F. Thus the successful storage of LNG requires very low (cryogenic) temperatures and extremely efficient thermal insulation materials. Even then, periodic venting is required to prevent pressure buildup. On the other hand, significant amounts of methane can be stored at ordinary temperatures by compressing it to high pressures (CNG). Such fuel requires heavy-wall, high-pressure containers in order that a significant quantity of natural gas can be stored in a reasonable volume (e.g., at pressures of 1,000 to 2,000 psi).

The use of LNG or CNG as fuel for conventional spark-ignition engines is being investigated extensively. Results indicate that the use of such fuels could lead to substantial reductions in emissions.[14,33] Tests in California[34] showed that emissions of CO, NO_x, and HC from spark-ignition vehicles fueled with natural gas were well below any standards currently in effect or scheduled to go into effect. (See Table 3-1, Section 3, for a summary of these standards.) Of the six vehicles tested, only one emitted more NO_x than the 1974 California standard of 1.3 grams per mile. It should be pointed out that HC emissions were reported as hydrocarbons other than methane. This was done because of the very low value of relative reactivity assigned to methane on most reactivity scales.

Before serious consideration can be given to substituting LPG, LNG, or CNG for conventional motor fuels, reserves, logistics, and economics of such fuels must also be considered. The technologies and capital investments currently related to the utilization of conventional motor fuels have developed along with the automotive industry, and the supply, consumption, and investment related to such fuels are enormous in comparison with those of LPG, LNG, and CNG.

Maintaining cleanliness of the induction system (i.e., carburetor, intake manifold, and intake port area) of currently used, spark-ignition engines may reduce the tendency for CO and HC emissions to increase as mileage is accumulated.[35] One major domestic fuel manufacturer is now marketing a gasoline containing an organic additive package that not only prevents formation of induction system deposits, but may also remove pre-existing induction system deposits.[35] This additive reportedly has no significant effect on combustion chamber deposits, and will not increase the price of the fuel in which it will be available.

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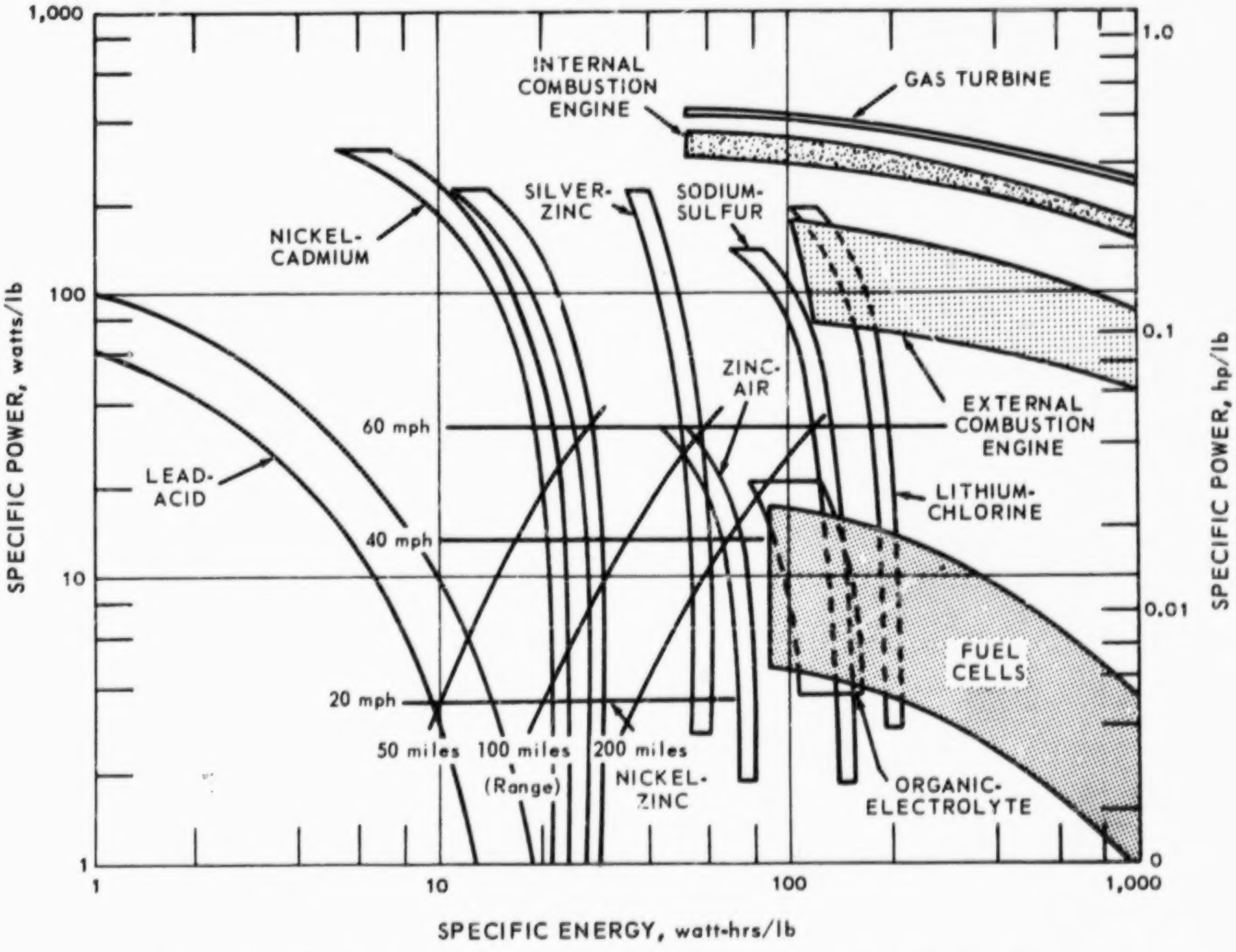
7. POSSIBLE SUBSTITUTES FOR CURRENTLY USED MOTOR VEHICLE ENGINES

States may wish to encourage the use of specific mobile power sources known for their low emissions. Research and development are under way toward improvement of historically proved engine concepts and applications of subsequent and developing technologies to concepts new to vehicle application.

Vehicle speed and range between stops to refuel or recharge are two very important considerations in the selection of a vehicle power source. Speed and range characteristics of several power sources are shown graphically in Figure 7-1. An engine or other power source has high specific power if it is lightweight, and



Note: Assumes 2,000 lb. vehicle, 500 lb. motive power source and steady driving. Power and energy taken at output of conversion device.

Figure 7-1. Vehicle requirements and motive power source requirements.[1]

large amounts of energy can be delivered to the drive wheels in a short period of time so that the vehicle can travel at high speeds. Also, an engine or other power source has high specific energy if it is lightweight, and large amounts of energy can be stored for later delivery, regardless of the rate at which it can deliver this energy. If a vehicle travels at high speeds, and thus requires high power, more energy per mile is used and the vehicle's range is reduced. An automotive power source should have both high specific power and high specific energy. The gas turbine and the internal combustion engine, as presently developed, have high capabilities in both speed (specific power) and range (specific energy).

Some of the concepts being advanced as possible substitute power sources for those currently in use are treated briefly herein. To the extent possible, features such as principles of operation, historical background, emissions characteristics, practical advantages, and costs are discussed.

7.1 AUTOMOTIVE GAS TURBINE

7.1.1 Principles

The gas turbine is a member of the internal combustion family of heat engines, operates on a modification of the Brayton cycle, and is the most promising substitute for currently used engines. In its simplest form, it consists of a compressor, combustion chamber (combustor), and a turbine, as indicated schematically in Figure 7-2. Inducted ambient air is compressed and delivered under pressure to the combustor, where energy is added by direct combustion of fuel sprayed into the chamber. Combustion occurs at essentially constant pressure. The high-temperature, high-pressure gas expands through the turbine and then exhausts to the atmosphere. Part of the shaft work developed by the turbine is used to drive the compressor, the remainder being the useful output work.[2]

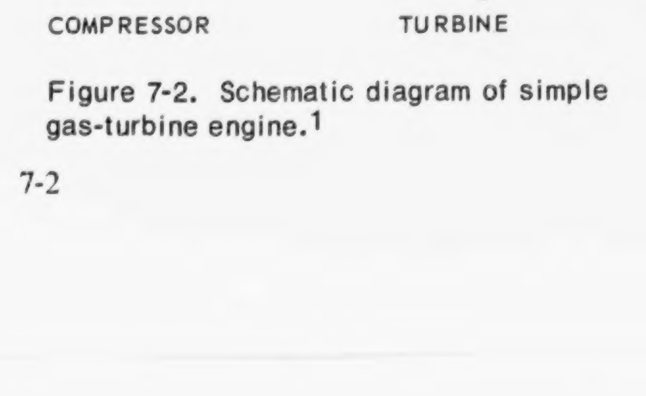


Figure 7-2. Schematic diagram of simple gas-turbine engine.[1]

Some of its operating characteristics require departure from these basic essentials for application of the turbine to a mobile vehicle. Compressor and turbine speeds are very high in load ranges and at idle. Exhaust temperatures are high, and air requirements are 5 to 10 or more times those of conventional gasoline engines for the same power level. Vehicle application requires a high degree of precision in manufacture, assembly, and rotor balancing to minimize vibration and possibilities of structural failure at the high rotational speeds. An adequate turbine housing is necessary to insure against exterior damage in the event of rotor or blade failure, and speed reduction is necessary between the turbine and the vehicle transmission. Regenerators or recuperators are employed to minimize exhaust heat loss, improve thermal efficiency, and relax requirements for exhaust ducting. Considerably more extensive air filtering and silencing is required than is necessary for a conventional gasoline automotive engine. In addition, the split shaft or free turbine configuration, indicated in Figure 7-3, is employed to improve operational flexibility.

7.1.2 Historical

Around the end of World War II, Chrysler in the United States and Rover in Great Britain began developing an automotive gas turbine. General Motors began around 1948; the first Rover turbine-powered automobile ran in 1949; and Ford began work in 1950. Principal early automotive turbine development problems were noise, poor fuel economy, lack of durability, and acceleration lag. Early turbine engines required approximately

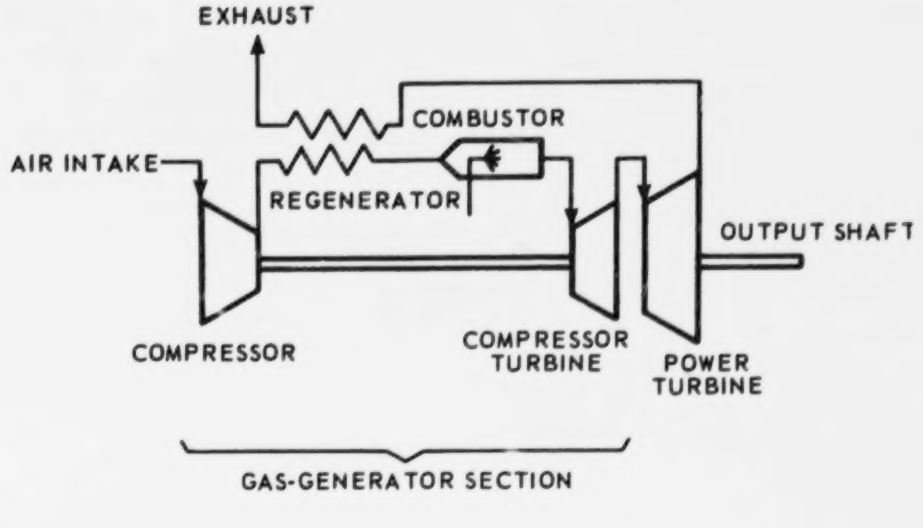


Figure 7-3. Schematic diagram of regenerative free-turbine engine.[1]

5 seconds from idle to full power, unacceptable in throttle response for passenger car use. In 1963, Chrysler undertook a 2-year consumer evaluation program in which 50 turbine-powered cars were lent for 3-month periods each to randomly selected families throughout the United States. According to press conferences, drivers considered the car "completely usable," although acceleration lag still was considered by some to be a problem. Gas turbines for truck application have been under development by Ford and General Motors since the early 1960's. Ford has reportedly been using turbine-powered super-transports in heavy-duty interplant transport. Turbine engines may be used in some 1970 model trucks, and Detroit Diesel division of General Motors[3] has announced availability of a heavy-duty turbine for truck application in mid-1971. It appears that heavy-duty trucks and buses may be the logical media for introducing the automotive gas turbine into the public market. In this application, the turbine represents a smaller percentage of total vehicle cost than in a passenger car. Its size permits an increase in payload; styling is less a factor in intake and exhaust considerations, and fleets usually have well-organized maintenance facilities and procedures.

7.1.3 Emissions

Emission data for gas turbines are extremely sparse by comparison with those for gasoline-powered motor vehicles. Of all the fuel-burning engines, however, gas trubine engines are considered to be among those that have the lowest emissions.[4] On a concentration basis, available information indicates emissions are extremely low. These figures cannot be compared directly with existing gasoline engine standards, however, because the total mass of gas turbine exhaust is many times greater than that for the gasoline engine of equivalent power. It appears, nevertheless, that gas turbine exhaust can be substantially cleaner than exhaust from present emission-controlled engines in regard to HC and CO mass emissions. Data for levels of NO_X emissions are less conclusive.

The General Motors GT-309 is a 280-horsepower, regenerative turbine developed in 1964. Emission data for it, converted to mass basis, indicate HC emissions to be about 16 percent and CO emissions to be about 12 percent of those of a 1968 vehicle equipped with a gasoline engine and exhaust emission control system. Emissions of NO_X, however, are approximately 1.75 times higher for the GT-309. A study of the Chrysler turbine car[5] indicates very low comparative emissions. Table 7-1 is based on this study.

7.1.4 Advantages and Disadvantages

In addition to its low emission characteristics, the gas turbine operates satisfactorily, but not interchangeably, on a variety of light hydrocarbon fuels, such as unleaded gasoline, diesel fuel, or kerosene. Other characteristics often attributed to it are light weight, greater simplicity, and reduced maintenance and service.[1]

The simple gas turbine can be a lightweight engine in terms of pounds of engine weight per horsepower delivered, but it also has high fuel consumption in urban operation and at idle. A gas turbine designed for variable speed and load is neither a simple nor a lightweight unit. The Chrysler gas turbine of 130 horsepower filled the available underhood space and weighed 410 pounds.[1] It is frequently assumed that a minimal transmission would be required for a multi-spool gas turbine because of its speed-torque characteristics. Thorough studies have always shown this assumption to be incorrect. Real progress with gas turbine power trains can be expected only when suitable transmissions are properly integrated with the gas turbine to capitalize on its advantages and overcome its disadvantages.[1]

The volume of air required by the gas turbine engine to hold turbine inlet temperature to a value that will not damage the turbine requires larger components throughout the air handling system than would otherwise be necessary. Air filters and silencers are large. Power output is affected significantly by inlet air pressure drop, which calls for a large filter-medium area. Dust passing the filters and blown through the turbine tends to erode components subject to the impact of dust particles. Operation under many conditions would require high-efficiency filtration. Exhaust ducting must be large to handle the volume of exhaust from the turbine with a small pressure drop.

Diagnosis of engine problems, maintenance, and service would undoubtedly require special training, equipment, and reorientation of service facilities. Maintenance and assembly at the present average-skill-level of automobile mechanics would be out of the question. Airlines have developed years of experience with aircraft maintenance programs, and aircraft turbines have shown time increments between major overhauls never attained by reciprocating engines. Aircraft engines do not operate in the stop-and-go-type service, nor in some of the adverse environments experienced by the

Table 7-1. EMISSION DATA FOR CHRYSLER TURBINE CAR – COLD-START, COMPOSITE-CYCLE, DYNAMOMETER TESTS[5]

	Exhaust emissions		
	HC	CO	NO_x
Pounds per mile (NDIR[a])	0.0020[b]	0.0155	0.0041
Pounds per mile (HC by FID[a])	0.0036[b]		
Grams per mile – gas turbine	0.91	7.03	1.86
Grams per mile – gasoline engine equipped with 1968 exhaust emission control system (NDIR)	3.43	35.10[c]	6.76[c]

[a] Abbreviations indicating type of sampling equipment: NDIR – non-dispersive infrared analyzer, FID – flame ionization detector.

[b] Hydrocarbon emissions measured by FID and converted to NDIR using factor of 1.80.

[c] Source – NAPCA – see Table 3-3.

motor vehicle. It is reasonable to assume, though, that gas turbines in road vehicles might show comparable development, provided that necessary service and maintenance facilities are reoriented.[1]

7.1.5 Costs

Estimated costs for a gas turbine in production vary widely. Unfortunately, there is no way of relying on gas turbine use in other fields of application to estimate its probable cost, because gas turbines are not in mass production. Small gas turbines for aircraft propulsion in the 500- to 800-horsepower class are produced in quantities of about 500 per month and are reported to sell for about $25 per horsepower.[1] At the other end of the scale are estimates of $2 to $4 per horsepower.[2,6] For a 250-horsepower gas turbine on these bases, the corresponding price range is $500 to $6,250. An auto manufacturer's estimate of approximately three times the cost of a conventional reciprocating engine represents a price increase of approximately $1,000 to $1,500 for the average family automobile.

7.2 ROTARY COMBUSTION CHAMBER ENGINE

7.2.1 Principles

The Wankel is the most prominent example of the rotary combustion chamber engine, having received more attention and development effort than any other. It employs a three-lobed member rotating within the confines of an epitrochoidal surface, the spaces between the two constituting a series of rotating combustion chambers. It uses gasoline fuel on a four-sequence cycle: intake, compression, power (expansion), and exhaust, as shown in Figure 7-4. Valving of the air-fuel charge and exhaust gases is accomplished through ports uncovered in sequence by the rotor. Power is taken from the rotor shaft. It can be built in multiple power increments by stacking individual power elements on a single shaft.

7.2.2 Historical

Concepts for rotary combustion chamber engines are numerous,[7,8] and many configurations are possible. Dr. Wankel reviewed and analyzed a great many.[9] It is interesting to note that his is the only one which has had any degree of commercial success. It has achieved limited acceptance in Europe and Japan in small cars, and has been promoted in the United States by the licensee for small utility tools, stationary power plants, aircraft, and marine applications.

7.2.3 Emissions

Emission characteristics are not generally available, especially for any operating cycle corresponding to the Federal seven-mode cycle. Theoretically, HC emission concentrations for an uncontrolled version would be higher than those of the conventional gasoline engine, because of the high quench characteristics of the long combustion chamber with its high ratio of surface area to volume.[10] The close proximity of the combustion chamber walls removes heat from the flame front as combustion propagates down the length of the chamber, slowing the rate of flame propagation and lengthening the required total time for combustion. At the same time, the high exhaust temperatures may indicate some afterburning effect. Another factor tending to increase emissions is the flow of blowby directly to the exhaust instead of to a crankcase. Two foreign manufacturers, however, have built versions with controls that have fulfilled Federal certification requirements.

7.2.4 Advantages and Disadvantages

By avoiding use of reciprocating members such as pistons and connecting rods, the rotary combustion chamber engine operates smoothly and is easily balanced. As a result, it can operate at high speed with minimum vibration. Power-to-weight and power-to-volume ratios are comparatively high, yielding a relatively high-power engine in a small package. Rotor sealing, seal life, and spark plug life have been problems with some engines. Manufacturing and servicing present

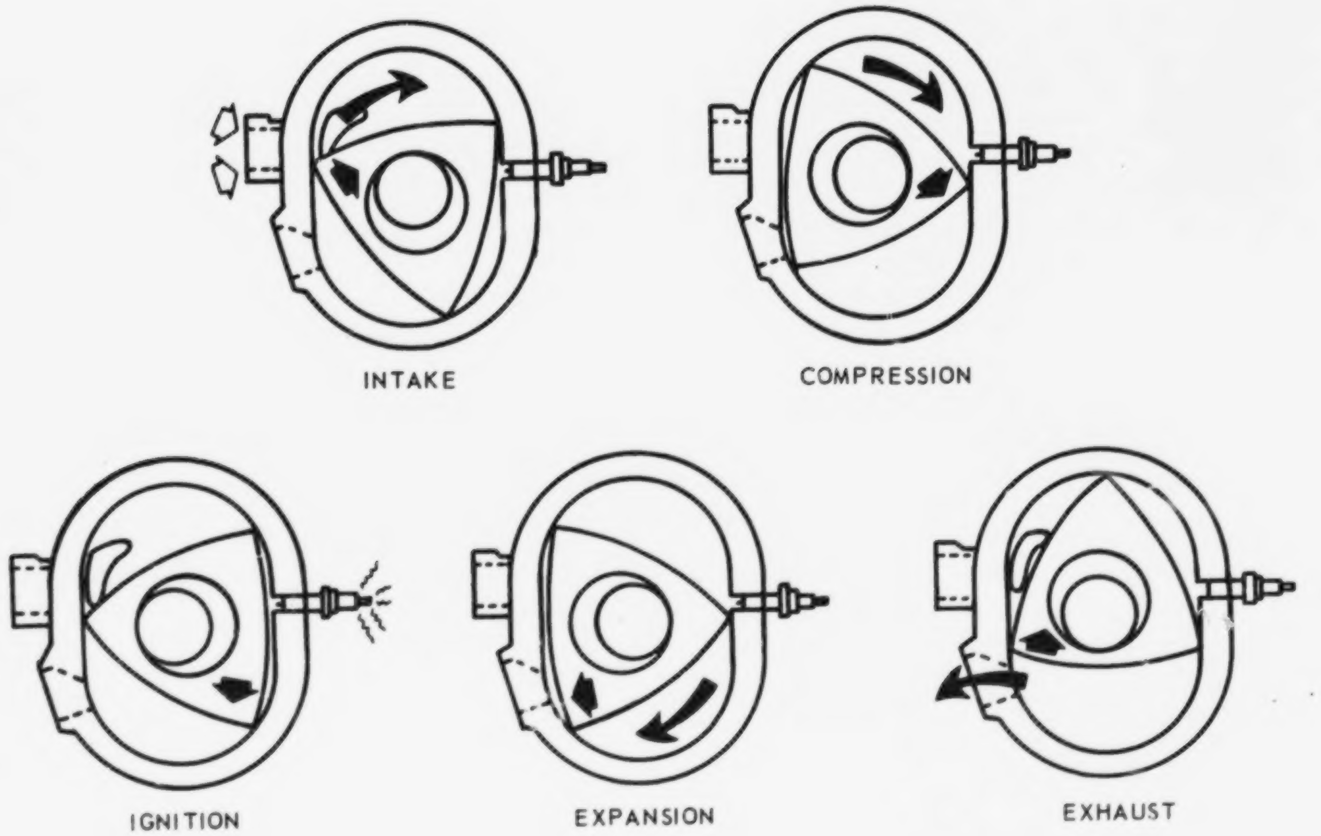


Figure 7-4. Sequence of Wankel rotary engine cycle events.

problems not encountered with the conventional gasoline engine. The epitrochoidal combustion and rubbing surface of the outer member is not a simple figure of revolution and requires special tooling for manufacturing and for rebuilding in service.

7.2.5 Costs

One source includes a questionable estimated of $4 per horsepower for the rotary combustion chamber engine,[1] which is at the high end of the ranges of costs estimated for the conventional gasoline engine. Assuming a cost of approximately 30 percent over the current gasoline engine, the additional cost to the consumer for the rotary combustion chamber engine might be estimated at $600 to $900.

7.3 STEAM ENGINE

7.3.1 Principles

The automotive steam engine (Rankine cycle) is an external combustion engine in which high-pressure steam or some alternative working fluid vapor is expanded in either a turbine or a positive displacement (i.e., piston-type) expander to produce work.[11,12] Figure 7-5 is a schematic of a typical Rankine cycle engine. Liquid moves at low pressure from the reservoir through the high-pressure liquid pump, then at high pressure through a heater, where it picks up heat from the expander exhaust. The liquid then moves at high pressure through the vapor generator, where fuel combustion converts it to superheated vapor. Metered into the expander, the superheated vapor expands to low pressure and temperature and does work by giving up energy in the expander. It then moves through the liquid heater where it gives up more energy, is converted to liquid in a condenser (typically air-cooled) and returns to the reservoir through a condensate pump. This is a closed system in which the working fluid is not allowed to escape, but is continuously reused.[2]

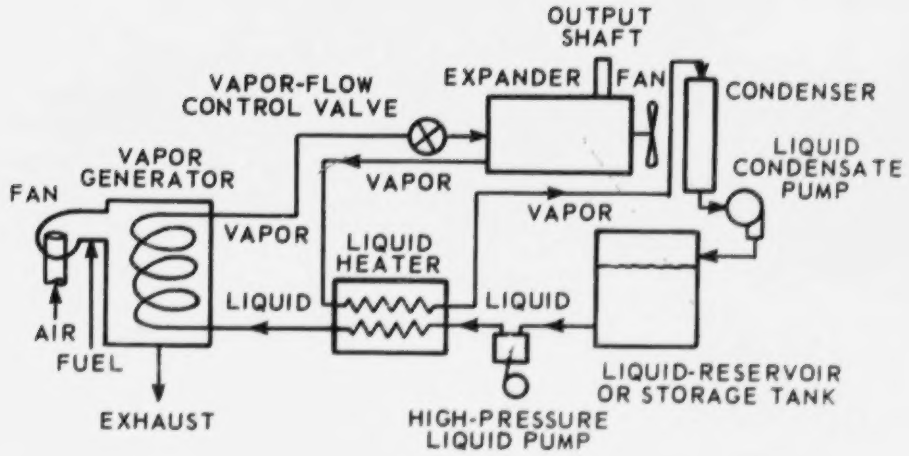


Figure 7-5. Schematic of typical Rankine cycle steam engine components.[2]

The majority of recent automotive vapor engines have piston-type expanders and use water as the working fluid, although some experimental work has been done with Freon and specially compounded fluids. Boilers are "once through" types, which give good throttle response and rapid warmup from a cold start. Conventional hydrocarbon lubricants are used, requiring separation from the working fluid to avoid boiler fouling. The possibility of freezing in cold weather is still a problem.

7.3.2 Historical

Use of Rankine cycle engines dates from 1827 or earlier, when primitive steam engines powered coaches. Stanley Steamer, Locomobile, White, and Doble cars were sold in the late 1800's and early 1900's. The Stanley Steamer was the most popular of 126 different makes produced during the period. It was in production from 1899 through 1925, reaching a production peak of 2,500 vehicles in 1910. Most of the early steam cars used a large boiler and a noncondensing system. Large quantities of water necessitated by this system required as much as a half-hour heating from a cold start to become operable. Stanley introduced a condenser in 1915.

Perhaps the most advanced steam car was the Doble, the last of which was build in 1930. It used a four-cylinder engine rated at 150 horsepower in a condensing system supplied by an electronically controlled, monotube boiler which could come up to pressure within 30 seconds.[2,13]

The only automotive steam power plant that has been offered for general sale in recent years is the Williams model. One experimental, 130-horsepower recent installation by General Motors is shown in Figure 7-6. Table 7-2 contains data for several automotive steam engines built or studied since 1950.

7.3.3 Emissions

Table 7-3 is a compilation of emission data for various external combustion engines, including three steam engines. The basis (driving cycle) under which these data were obtained is not known. Concentrations are obviously quite low, however.

7.3.4 Advantages and Disadvantages

Aside from its low emissions characteristics, the steam engine has good low speed torque, which would not necessarily eliminate the need for a transmission, but might simplify it. Its multifuel capabilities are also an advantage, which as yet have probably not been explored to full potential. The engine is quiet and apparently durable. A Doble car reportedly has run 800,000 miles.[6] The steam engine system, at low production, has been expensive to manufacture and, historically, has suffered from lack of service and repair facilities by comparison with the gasoline-powered car. The complete system is bulky, complicated by need for an auxiliary power

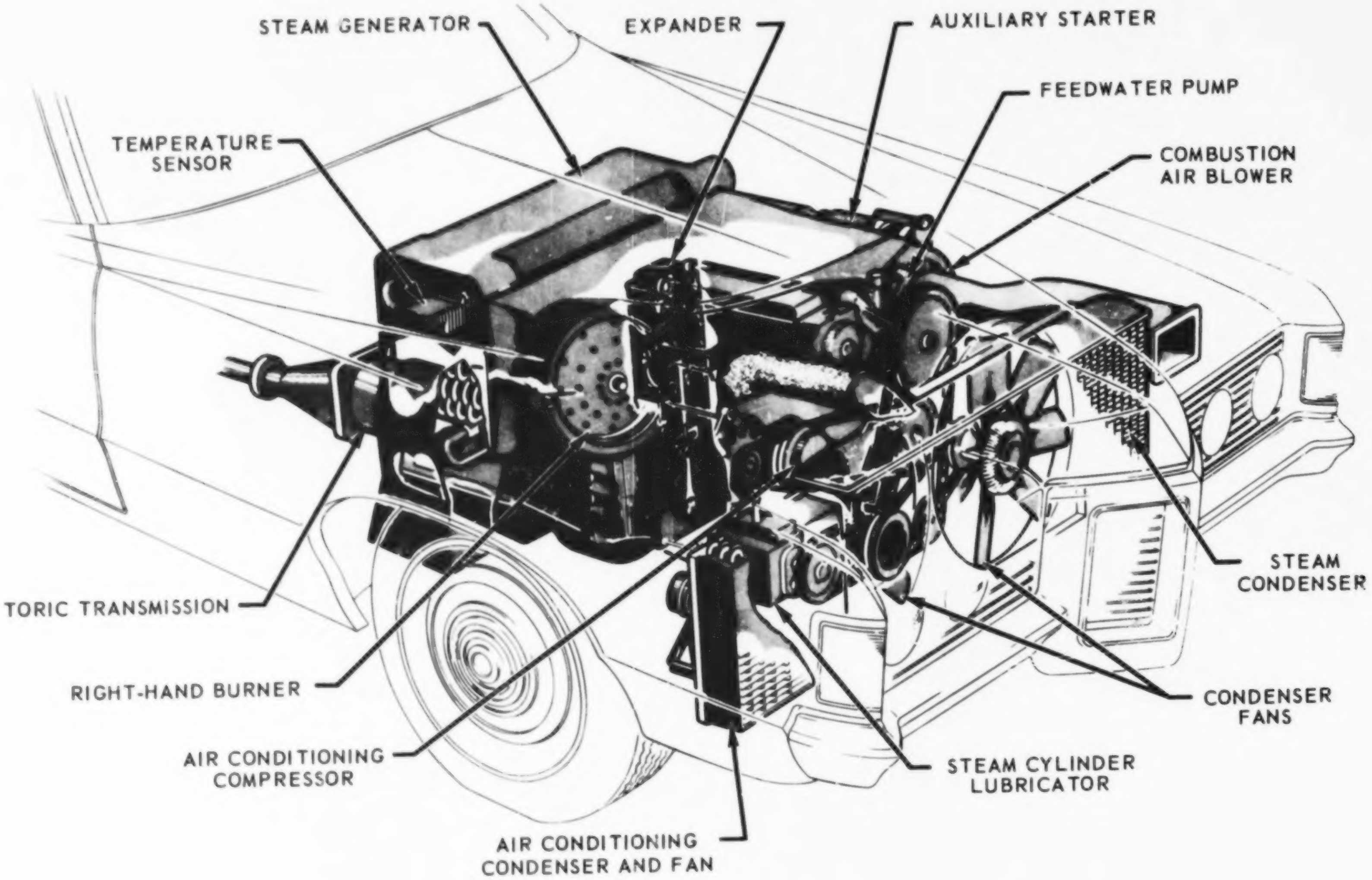

STEAM GENERATOR
EXPANDER
AUXILIARY STARTER
FEEDWATER PUMP
TEMPERATURE SENSOR
COMBUSTION AIR BLOWER
STEAM CONDENSER
TORIC TRANSMISSION
RIGHT-HAND BURNER
CONDENSER FANS
AIR CONDITIONING COMPRESSOR
STEAM CYLINDER LUBRICATOR
AIR CONDITIONING CONDENSER AND FAN

Figure 7-6. Steam engine installation.[3]

Table 7-2. DATA ON SEVERAL AUTOMOTIVE STEAM ENGINES EITHER BUILT OR STUDIED SINCE 1950[2]

Developer or researcher	Engine reference	Rating, hp at rpm	Rated $\frac{\text{pressure, psia}}{\text{Temperature, °F}}$	Specific weight, lb/hp(s)	Specific volume ft^{3}hp(s)	Maximum efficiency, %	Startup time[a] sec	Torque ratio[b]	Power-surge ratio[c]	Specific cost, $/hp(s)
Williams Engine Co.	49	150 at 2400	$\frac{1000}{1000}$	5.4	0.14	--	PO<30	3.4	1.67	44
McCulloch Corp.	50	120 at 1200	$\frac{2000}{900}$	8.0	--	23	FPO<30	--	1.25	--
Gibbs Hosick Trust	51	60 at 2500	$\frac{2000}{850}$	--	--	--	--	2.3	--	--
Richard J. Smith	52	250 at 6000	$\frac{1000}{700}$	--	--	28	FPO-14	1.8	--	--
USAMERDC	--[d]	3 at 3600	$\frac{700}{850}$	20.0	--	19	PO-120	--	--	--
Thermo Electron Engineering Corporation	53[e]	100 at 1680	$\frac{1200}{1250}$	5.0	--	28	--	1.1	--	--
Microtech Research Co.	54[e]	175	$\frac{1500}{1100}$	17.2	0.67	16	FPO-500	--	--	--
General Dyanamics/Convair	55[e]	500	$\frac{1200}{1000}$	--	0.16	22	--	--	1.5-2.0	--
S. W. Gouse, Jr.	25,56[e]	--	--	5-10	--	25-30	--	--	--	3(?)
Battelle/Northwest	57[e]	50	$\frac{2500}{670}$	--	--	24	FPO<10	--	--	--

[a] PO = time to power output; FPO = time to full power output.

[b] Torque ratio = the ratio of stall torque to rated torque.

[c] Power-surge ratio = the ratio of short-term, "burst," power to continuous rated power.

[d] Estimated parameters for steam engine currently under test by United States Army Mobility Equipment Research and Development Center. This engine is not for vehicular application, but is included to illustrate state-of-the-art for small steam engines.

[e] Paper studies only.

Table 7-3. EMISSION DATA[a] FOR EXTERNAL COMBUSTORS ASSOCIATED WITH STIRLING ENGINES AND STEAM ENGINES[2]

Fuel	Type of equipment	Reference	CO, %	HC, ppm	NO_x, ppm
No. 2 diesel	GM Stirling engine – 10 hp[b] with combustion air preheater	3	0.008	2 2	500
Kerosene	Williams steam engine	--[c]	0.05	20	70
JP-4	Thermo-Electron steam engine	--[c]	0.001	--	110
	Steam engine; developer's name withheld by request	--[c]	0.3	30-40	25-35
Diesel fuel	Philips Stirling engine – 80 hp[d] with exhaust-gas recirculation	--[c]	0.017	--	38

[a] When comparing the data in this table with those for gasoline engines on a relative mass-emission-rate basis, the data in this table should be roughly doubled to account for the higher air/fuel ratio generally used with external combustors.

[b] Operated at 25:1 air/fuel ratio.

[c] Data supplied by organization developing engine.

[d] Operated with 50 percent of combustion air from recirculated exhaust gases.

system to drive accessory equipment when the engine is not turning. Possible freezing, or lack of a suitable substitute for water to operate at efficient temperature and pressure ranges, is still a problem, and separation of the lubricant from the working fluid is difficult. The possibility of an explosion or serious vapor leak may be a safety hazard to be considered carefully. Since it is costly to provide a condenser capable of condensing all the working fluid at full load, makeup working fluid must be added to most engines periodically.

7.3.5 Costs

At the present state of development, costs are impossible to fix accurately. One reference sets the cost of an automotive steam engine system at $4 to $6 per horsepower.[2] A recent developer reported a cost of $1,200 for the stainless steel tubing alone for his flash-type boiler, which is more than the total cost of a current conventional V-8 engine.[14] These figures illustrate the inexactness associated with establishing a production price for an undeveloped item. The Williams Engine Company of Ambler, Pennsylvania, was taking orders in 1967 for a complete power plant at $6,450 or a Chevelle automobile with steam system installed for $10,250. These prices were for lots of ten engines.[2]

7.4 ELECTRIC DRIVES

7.4.1 Principles

An electric drive system consists essentially of an electric power source, a drive motor, and means of controlling energy flow from the power source to the motor in response to requirements of vehicle operating modes. All three components must be considered in evaluating the electric vehicle, but the electric power source seems to be the most critical with respect to development of a practical electric vehicle.

Three types of electric power systems are being explored: (1) battery, (2) fuel cell, and (3) hybrid.[15] Hybrid concepts include engine/battery combinations in which an engine continuously recharges a battery, fuel cell/battery combinations in which the fuel cell continuously recharges a battery, and a battery/battery combination in which a primary, or nonrechargeable battery, continuously recharges a secondary, or rechargeable battery. The fuel cell and hybrid systems (battery/battery to only a limited extent), at least theoretically, are capable of extended operation, depending upon fuel replenishment. The battery system must be recharged periodically.

The electrochemistry of the battery and fuel cell is similar. Figure 7-7 illustrates the common lead-acid battery, and Figure 7-8, a simple hydrogen-oxygen fuel cell.[16,17] As illustrated in Figure 7-7, an electrical load applied across the anode and cathode results in a flow of electrons through the load, and within the battery from the lead peroxide cathode to the lead anode. Reaction with sulfuric acid results in formation of lead sulfate on both and, eventually, battery exhaustion. Reactions are reversed and the lead is regenerated at the anode, and the lead peroxide at the cathode, when the battery is recharged. In the fuel cell in Figure 7-8, anode and cathode material (hydrogen and oxygen) is supplied continuously, avoiding the necessity for recharging.

One engine/battery hybrid power system, which to date is only a mockup, is illustrated in Figure 7-9. The system includes six 12-volt batteries, a 35-cubic inch displacement, two-cylinder engine, a flywheel alternator for recharging the batteries, a series-wound direct-current motor, an electronic control system, and an onboard charger that can be connected to an external 115-volt alternating-current power source. Design objectives are 2,100-pound weight, 60-mph maximum speed, and acceleration from 0 to 40 mph in 12 seconds and 0 to 60 mph in 28 seconds. The vehicle can operate in either all-electric or hybrid mode.

7.4.2 Historical

Electric vehicles are not new. The first experimental versions were built in the 19th century.[18,19] Rapid improvement of internal combustion engines soon made most electric cars obsolete.[18,20] The present state-of-the-art battery electric vehicles for practical

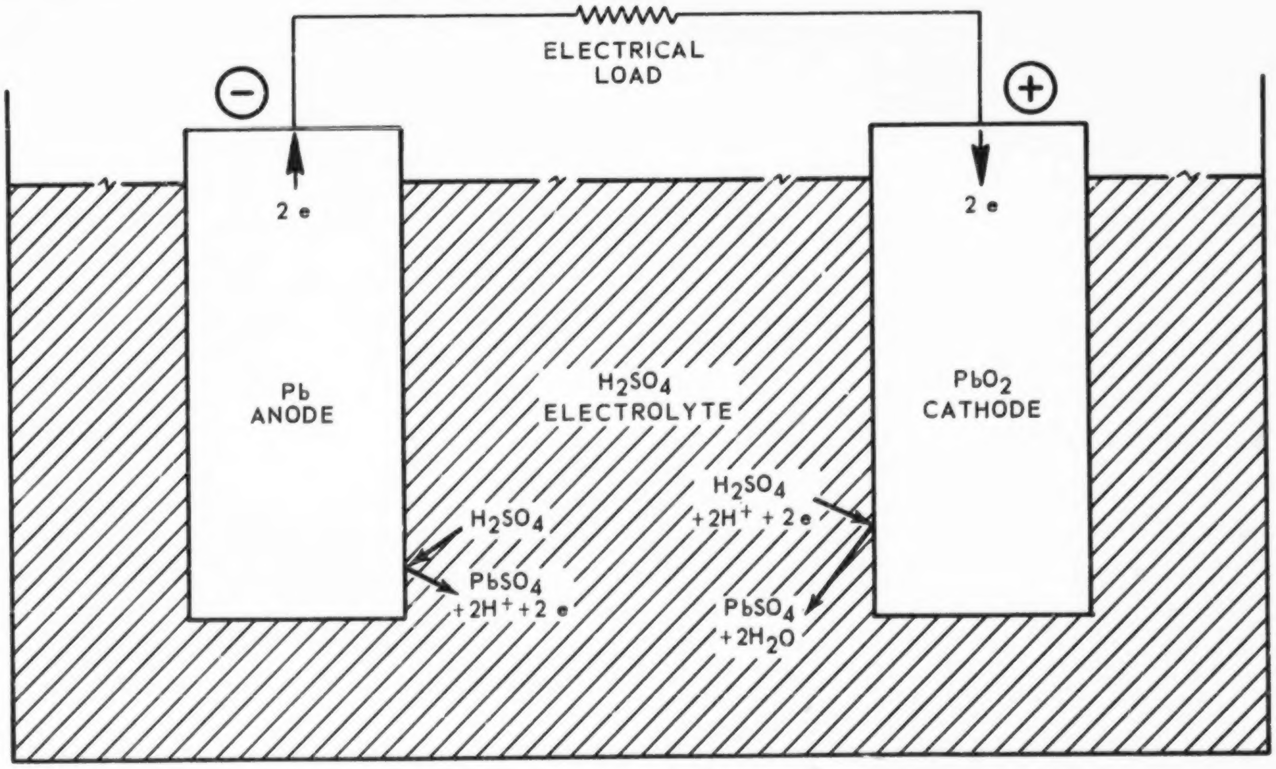


Figure 7-7. Illustration of lead-acid storage battery.

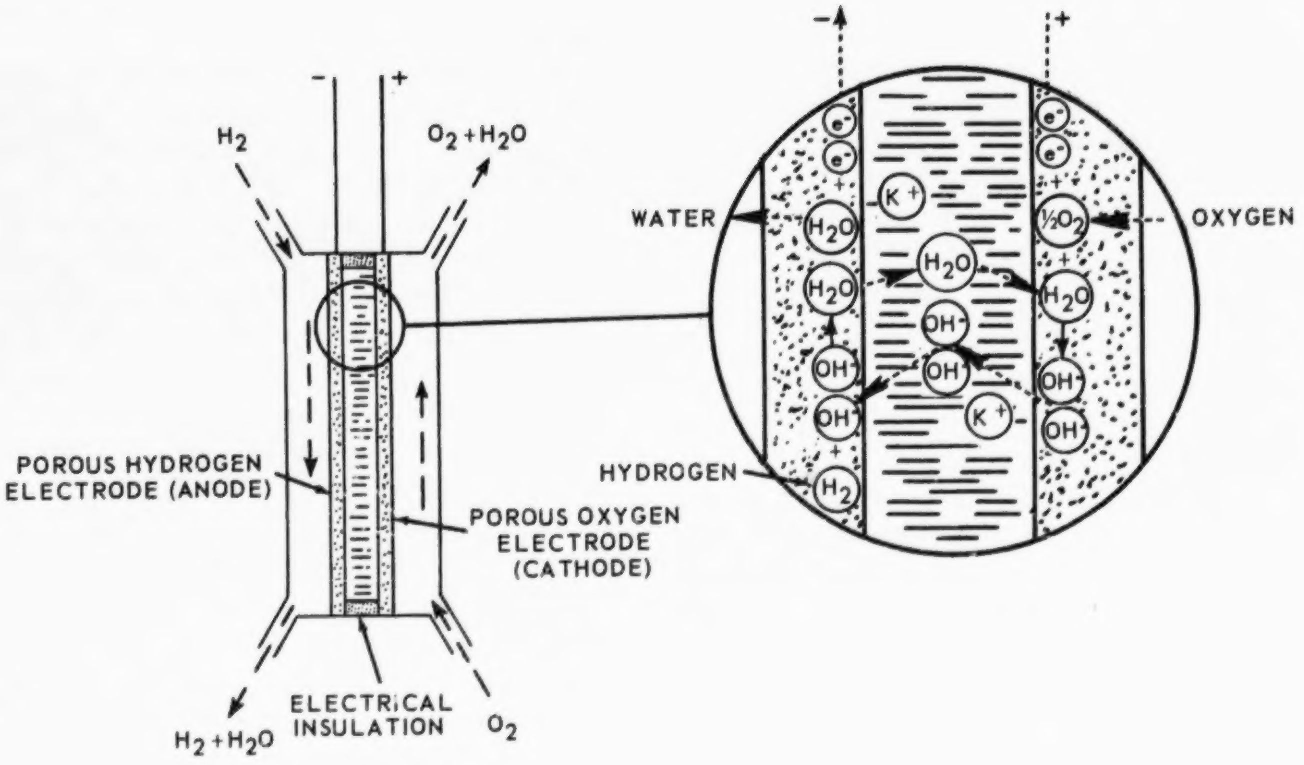


Figure 7-8. Illustration of a simple hydrogen-oxygen fuel cell.[16]

domestic use are chiefly low-performance and short-range vehicles that utilize lead-acid batteries or hybrid systems.[16,20,23-30] Most are experimental.

Use of electric vehicles in the United Kingdom has been commonplace throughout this century, and has increased rapidly since World War II.[31] Powered by lead-acid batteries, the vehicles are used primarily for multistop delivery service, although attention is now being given to development of a short-range passenger car.

7.4.3 Emissions

Battery-powered vehicles are generally regarded as being free of contaminating emissions. Lead-acid batteries emit hydrogen and oxygen, and an accumulation of these might result in a fire or explosive hazard. Emissions from other types would depend on the materials used.

Fuel-cell energy sources would reduce emissions of CO, NO_x, and hydrocarbons, although some would probably be emitted, depending upon the materials used. Hybrid systems using Stirling cycle or internal combustion engines would emit some CO, NO_x, and HC, although at a lower level, because the engines could be designed to operate at conditions least conducive to emission formation.

7.4.4 Advantages and Disadvantages

Freedom from emissions appears to be a major advantage of the electric vehicle, although users in the United Kingdom claim greater reliability and durability, and lower cost as compared to gasoline-fueled delivery vehicles. Quietness and smoothness of operation are additional advantages.

Some apparent disadvantages are short operating range, inconvenience imposed by necessity to recharge batteries, relatively heavy propulsion system, poor high-speed performance, and higher initial cost. Vehicle safety is possibly impaired. It is a certainty that vehicles are involved in collisions; hazards from spilled electrolyte and electrical fires are a possibility when a collision occurs.

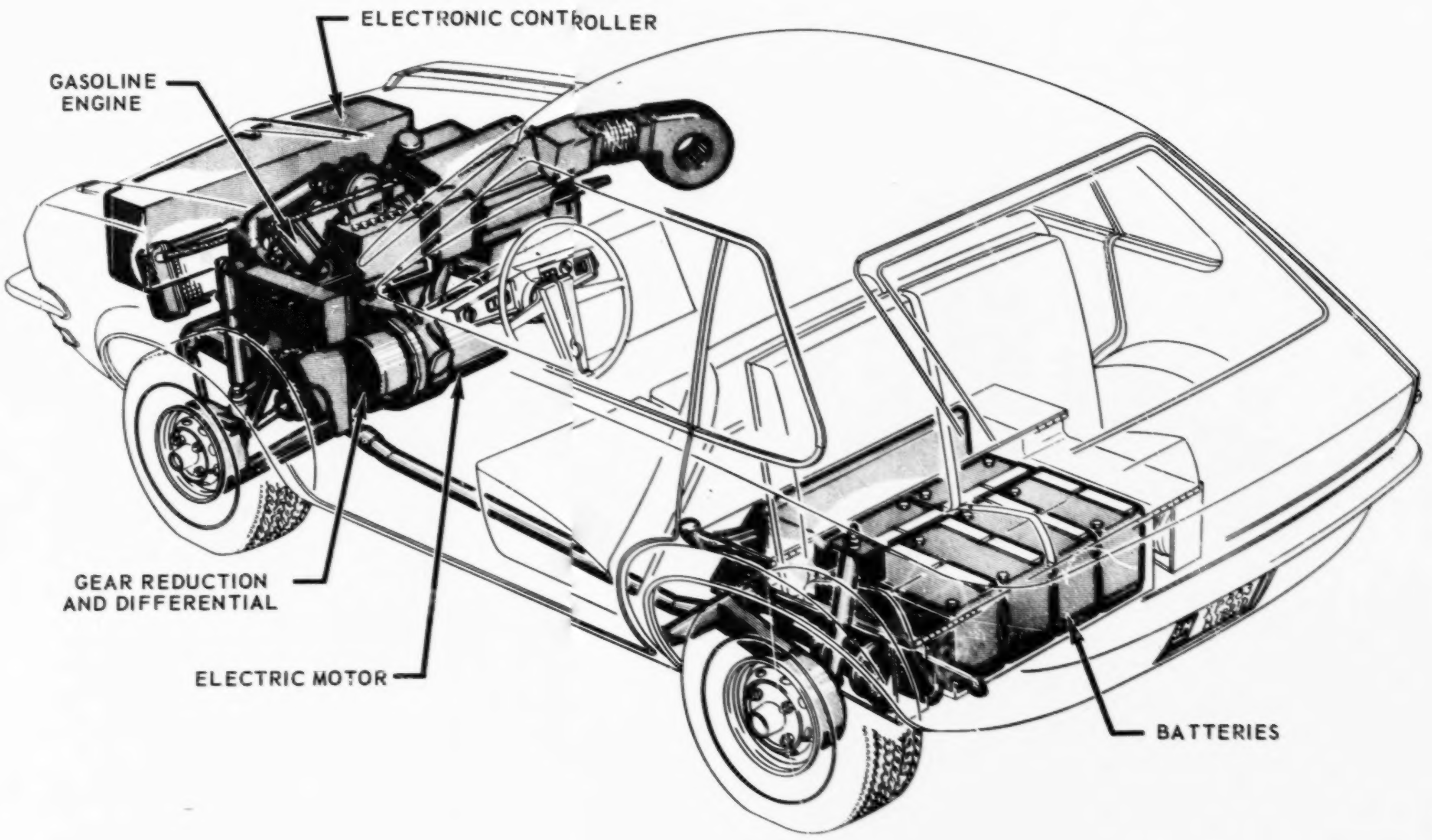

ELECTRONIC CONTROLLER
GASOLINE ENGINE
GEAR REDUCTION AND DIFFERENTIAL
ELECTRIC MOTOR
BATTERIES

Figure 7-9. Phantom view of General Motors XP-883 experimental hybrid car.[3]

No present, fully-developed, secondary battery system is capable of powering a full-sized family automobile with performance, range, and cost to match its internal-combustion engine counterpart.[15] The objective of future development is a secondary battery with an energy density of at least 100 to 120 watt-hours per pound and 100 watts per pound power density.[15,20,30] This is in sharp contrast to the lead-acid storage battery, which has an average energy density of 8 to 13 watt-hours per pound and a maximum power density of 32 watts per pound.

7.4.5 Costs

Operating costs of battery-powered vehicles will depend upon the local utility rates. One reference estimates that a small electric car might consume 5,270 Btu of energy per mile.[31] The most favorable electrical rates for battery recharging would result in an electrical cost range of 0.5 to 1.5 cents per mile. Replacement cost for batteries is expected to add 2 to 4 cents per mile. By comparison, a similar sized gasoline-powered vehicle was estimated to cost 1.24 cents per mile for fuel, including taxes.

Testimony at hearings before Congress regarding electric vehicles revealed that in England over 48,000 lead-acid battery-powered vehicles were in use in 1966, primarily for multistop delivery service.[29] It was stated that the primary reason for the use of electric vehicles is the economic advantage that they offer over gasoline-fueled vehicles. High petroleum costs and a tax advantage contributed to the economic advantage of electrics.

At the present state of development, costs of fuel cells are very high and prohibitive for use in automobiles at this time.[15]

7.5 FREE-PISTON ENGINES

7.5.1 Principles

Basically, the free-piston engine is a two-stroke, uniflow-scavenged, opposed-piston diesel engine that is supercharged by directly connected reciprocating compressor pistons (Figure 7-10). All of the work produced in the diesel (or power) cylinder is absorbed by the compressor pistons and mechanical friction. The compressor pistons store up energy in "bounce chambers" to stop piston

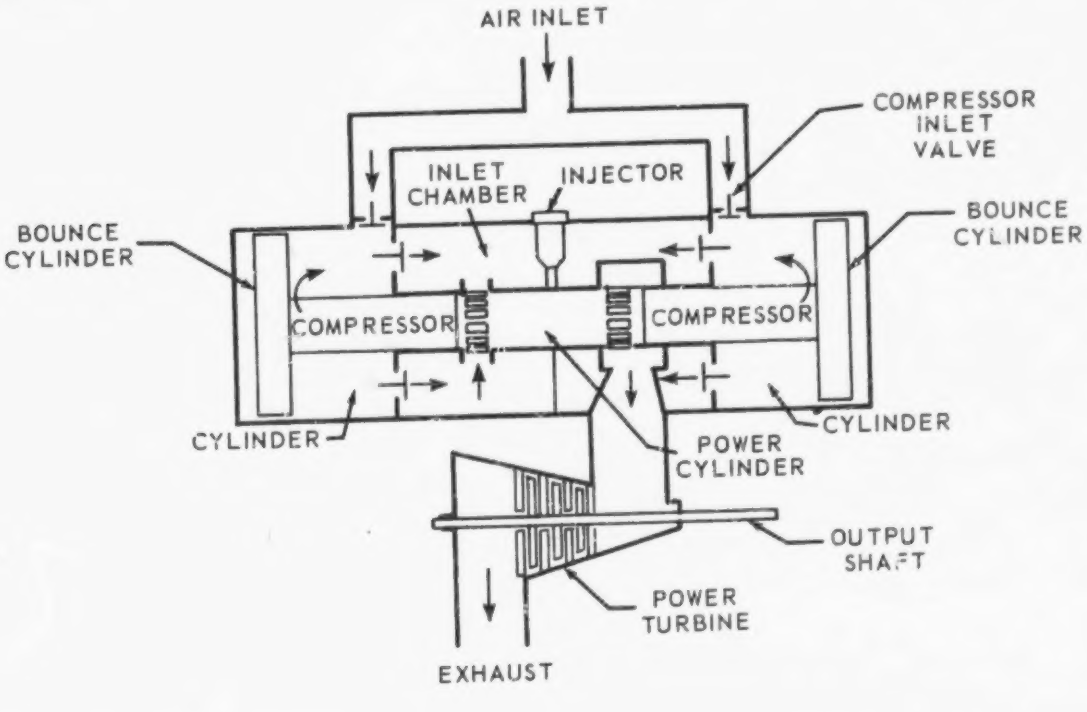


Figure 7-10. Schematic of free-piston engine serving as a gasifier to drive a power turbine.

motion at the end of the outward piston stroke and to return the pistons to a center position during the inward compression stroke.

For a vehicle engine, the free-piston engine would be essentially a gasifier to provide hot, high-pressure gas as a working medium to a power turbine. As such, it would correspond in function to the compressor and combustion sections of a gas turbine engine.

7.5.2 Historical

Free-piston engines have been used in limited numbers in Europe as compressors for many years. In the last 2 decades, efforts have been directed toward their development as a gasifier combined with a power turbine to furnish power for ships, locomotives, pumps, electrical power generators, and vehicles.[31-33] They have not had significant acceptance in any vehicle in the United States.

7.5.3 Emissions

It is doubtful that there are any data regarding emissions characteristics for the free-piston engine as a motor vehicle power plant in any driving mode. The combustion process, pressures, temperatures, etc., are similar to those of a highly turbocharged diesel engine, and emission characteristics should be similar.

7.5.4 Advantages and Disadvantages

As a part of a vehicle power package, the free-piston engine is comparatively bulky and heavy, although a wide range of fuels can be used. Starting requires an auxiliary air source since there is no mechanical way to drive the pistons. Maintenance is, reportedly, higher than for a diesel engine. The added complications of a free-piston engine are difficult to justify technically or economically by comparison with a highly turbocharged diesel engine.

7.5.5 Costs

Production costs are not available for a free-piston engine; it is expected, however, that if a free-piston engine were developed for vehicular propulsion, costs would exceed that of a present diesel engine.

7.6 STIRLING ENGINE

7.6.1 Principles

The ideal thermodynamic cycle corresponding to the Stirling engine theoretically produces the highest thermal efficiency that can be obtained for given temperatures of the heat source and sink. How closely an actual Stirling engine approaches this idealized cycle depends on (among other things) how efficient (and therefore how heavy, bulky, and expensive) the regenerator is. Moreover, the required addition and rejection of heat at constant volume and isothermal compression and expansion can only be approximated in an actual engine.

The Stirling engine is an external combustion "air" engine in which energy is added to or removed from the closed-cycle working fluid through heat exchangers. The concept basically employs two pistons operating in either the same or separate cylinders. One piston does not change the volume of active working fluid in the system, but serves merely to move the working fluid in and out of heat exchangers where energy is either added or removed. The other piston allows the working fluid to expand and produce work and also compresses the working fluid prior to the addition of energy.[34,35]

7.6.2 Historical

The principles of the Stirling engine have been known for more than a century. Robert Stirling first patented an engine in 1816. In more recent years, development of the engine has been pursued by Philips Research Laboratories of Eindhoven, Netherlands. In 1958, Philips and General Motors entered into a cooperative program to develop the engine for commercial and military applications.[35]

7.6.3 Emissions

The low exhaust emission level from the external combustor of the Stirling engine is one of its most attractive features. Both CO and HC are at very low levels. Table 7-3 shows measured emission levels for the General Motors and the Philips Stirling engines.

7.6.4 Advantages and Disadvantages

Several advantages are credited to the Stirling engine. Exhaust emissions are low, and engine thermal efficiency is higher than spark-ignited engines and comparable to the diesel engine. The noise level of a Stirling engine is low since there is no appreciable combustion noise, as in the case of an internal combustion engine, and the movement of the mechanical components could be relatively quiet. A wide range of fuels can be used.

The Stirling engine is a contender for use in hybrid engine designs where it could be used to drive a generator to supply electrical power to storage batteries, which in turn would propel the vehicle by electric motors. The two power sources could be coupled together to provide power for peak demands.

A Stirling engine installed in a passenger car would be heavier, bulkier, more expensive, and less flexible than a conventional reciprocating engine. It has a relatively more complex drive mechanism that must be employed to move the pistons and extract power. Ideally, each piston must stop while the other piston moves its full travel in one direction or the other. This cannot be easily achieved in practice; and a compromise motion is attained with, for example, the rhombic drive in the General Motors Stirling engine concept, illustrated in Figure 7-11. The heat exchangers required for an efficient Stirling engine are bulky, heavy, and expensive. For instance, the cooling radiator surface in one concept would be 2.5 times that required for a comparable internal combustion engine. The heater of this same concept is composed of small stainless steel tubes, which must be carefully welded to form gas-tight joints under high-temperature operating conditions. Further, a blower may be required to furnish air to the combustor.

7.6.5 Costs

No production costs of the Stirling engine are available; it is estimated to be significantly more expensive to produce than present automotive engines, however.

7.7 STRATIFIED-CHARGE ENGINE

7.7.1 Principles

The stratified-charge engine is an unthrottled, spark-ignition engine using fuel injection in such a manner as to achieve selective stratification of the air-fuel ratio in the combustion chamber. The air-fuel ratio must be in the ignitable range only at the spark plug, becoming fuel-lean away from it. The engine takes a full charge of air into the cylinders on each intake stroke, completely independent of power output. Power is controlled by increasing or decreasing the amount of fuel introduced into the cylinder to match the power demand on the engine. At low outputs, surplus air is not mixed with fuel, yet an ignitable mixture is obtained at the spark plug and combustion is initiated in normal fashion. Combustion progresses to the limits of the combustible mixture, where it is terminated.

7.7.2 Historical

Of the several stratification systems advanced, the Ford, Texaco, and Witsky have shown the greatest promise in the United States. Stratified-charge engines have operated in road vehicles experimentally.

7.7.3 Emissions

Normally, the stratified-charge engine does not exhibit less unburned hydrocarbons than a conventional gasoline engine. At part power, this is due to the fact that, although combustion is excellent in the stratified fuel cloud zone, some fuel diffuses into the surplus air zone prior to combustion. This mixture is too lean to burn and tends to raise the total level of exhaust hydrocarbons. CO levels are reportedly low and NO_x, high. Emissions data for any of the stratified-charge engines under active development are not considered consistent.

7.7.4 Advantages and Disadvantages

A principal objective in developmental efforts of stratified-charge engines has been improved fuel economy, especially at idle and

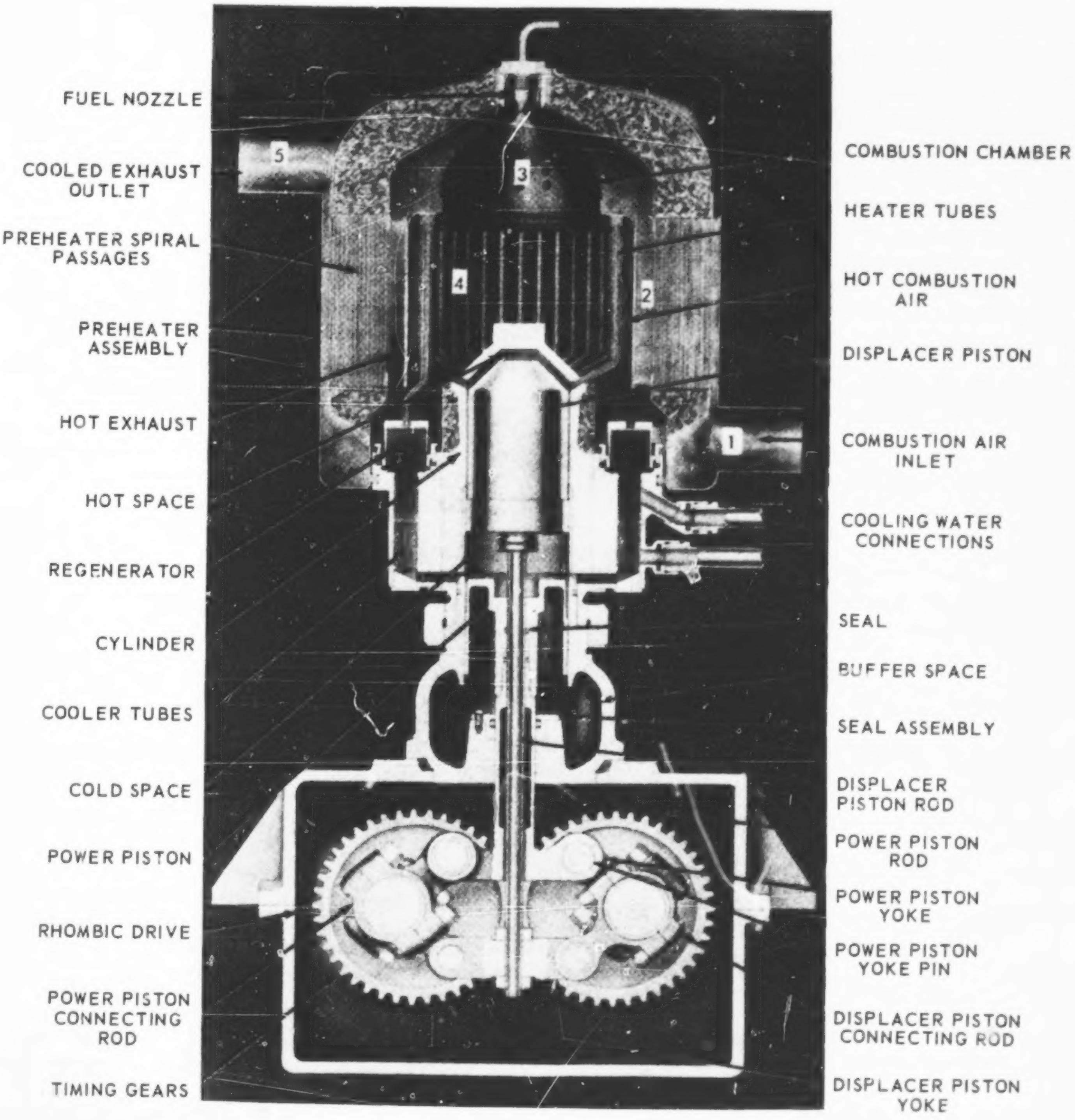

FUEL NOZZLE
COOLED EXHAUST OUTLET
PREHEATER SPIRAL PASSAGES
PREHEATER ASSEMBLY
HOT EXHAUST
HOT SPACE
REGENERATOR
CYLINDER
COOLER TUBES
COLD SPACE
POWER PISTON
RHOMBIC DRIVE
POWER PISTON CONNECTING ROD
TIMING GEARS
COMBUSTION CHAMBER
HEATER TUBES
HOT COMBUSTION AIR
DISPLACER PISTON
COMBUSTION AIR INLET
COOLING WATER CONNECTIONS
SEAL
BUFFER SPACE
SEAL ASSEMBLY
DISPLACER PISTON ROD
POWER PISTON ROD
POWER PISTON YOKE
POWER PISTON YOKE PIN
DISPLACER PISTON CONNECTING ROD
DISPLACER PISTON YOKE
5
3
4
2
1

Figure 7-11. Schematic drawing of Stirling thermal engine.[35] (Courtesy of SAE Transactions)

part load. This objective apparently is being achieved. Even though such engines have high compression ratios, they can operate on low octane, unleaded fuel, and yet provide excellent acceleration without overenrichment of the air-fuel mixture. Mixture distribution from cylinder to cylinder is good, and no air-fuel ratio mixture control is necessary to accommodate special power conditions. Ignition problems were encountered in earlier developmental stages, and apparently still exist, especially with respect to spark plug life. Fuel coking seems to contribute to this and to injector fouling.

7.7.5 Costs

Production costs are not available for the stratified-charge engine; it is estimated to be more expensive to produce than current automobile engines, however. Costs may be comparable to those of current engines equipped with fuel injection systems.

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8. REGIONAL EMISSION ESTIMATES AND EMISSION FACTORS FOR MOBILE SOURCES

8.1 ESTIMATING REGIONAL VEHICULAR EMISSIONS

Average emission factors and the vehicle miles of travel can be utilized to estimate motor vehicle emissions within a particular region.[1] The total emissions from all gasoline-powered motor vehicles in a region are a function of the emission factors, the vehicle miles of travel in the region, and the percent of travel that is urban. Assuming that the gasoline-powered vehicle makeup in the region is the same as the average national makeup (i.e., with respect to average vehicle age, make, engine displacement, etc.), and that the relative travel of gasoline-powered light- and heavy-duty vehicles is the same as the national average, the average national emission factors will apply equally well on the regional basis. Therefore, in order to estimate regional emissions, all that is needed are the vehicle miles of travel and the percent of travel that is urban.

The following equations can be applied to obtain regional emission estimates:

$$(1)\ TE = UE + RE$$

$$(2)\ UE = (UF)\,(VMT)\,(a)\,(k)$$

$$(3)\ RE = (RF)\,(VMT)\,(1 - a)\,(k)$$

where:

TE = Total emissions, tons/year
UE = Urban emissions, tons/year
RE = Rural emissions, tons/year
UF = Urban emission factor, grams/mile
RF = Rural emission factor, grams/mile
VMT = Vehicle miles of travel, miles/year
a = Fraction of travel that is urban
k = 1.1023×10^{-6} ton/g (a conversion factor).

Table 8-1 presents the emission factors necessary in equations (2) and (3) for calculating total emissions. Use of this method for predicting regional emissions presumes the following:

1. All distributions by population, age, and travel applicable nationally are applicable in the region.
2. The road route and average route speeds used in calculating national emissions are representative of the regional travel.
3. National average emission levels per vehicle apply in the region.

As an example, consider the hypothetical case of a region in which the number of vehicle miles of travel is estimated to be 10.2 billion miles in 1985, and the estimated fraction of urban travel is 0.80. To estimate the total CO emissions from gasoline-powered motor vehicles, all the presently established controls should be considered. Table 8-1 indicates that the urban vehicle emission factor (UF) for CO in 1985 is 25.7 g/mile and the rural vehicle emission factor (RF) for CO in 1985 is 10.7 g/mile. Substituting these values into the equations yields:

UE = (25.7 g/mile) 910.2×10^{9} mile/year (0.80) (1.1023×10^{-6} ton/g)
UE = 2.31×10^{5} ton/year
RE = (10.7 g/mile) (10.2×10^{9} mile/year) (0.20) (1.1023×10^{-6} ton/g)
RE = 0.24×10^{5} ton/year

Table 8-1. AVERAGE ON-THE-ROAD EMISSION RATES FOR GASOLINE-POWERED MOTOR VEHICLES[a] (grams/vehicle-mi)

Year	Hydrocarbon		CO		NO_x	
	Urban	Rural	Urban	Rural	Urban	Rural
1960	21.8	14.6	87.1	34.9	5.72	6.39
1965	20.4	13.2	87.6	35.6	5.76	6.53
1968	17.9	11.4	80.9	33.0	5.92	6.70
1970	14.6	9.49	67.9	28.1	6.27	7.10
1975	7.39	4.78	40.9	17.5	6.84	7.81
1980	4.20	2.65	27.6	11.9	7.08	8.18
1985	3.71	2.18	25.7	10.7	7.08	8.27
1990	3.69	2.18	25.6	10.8	7.06	8.31

[a] Includes cars and trucks, and applicable control systems in use as of 1971.

$$TE = UE + RE = 2.31 \times 10^5 \text{ ton/year} + 0.24 \times 10^5 \text{ ton/year}$$

$$TE = 2.55 \times 10^5 \text{ ton/year}$$

Hence, the estimate of total CO emissions in 1985 for the conditions stated is 2.55×10^5 ton/year.

Vehicle miles of travel for most cities are available as a result of the Federal Aid Highway Act of 1962,[2] which required cities of over 50,000 population to initiate a transportation study in order to qualify for Federal aid for road construction. Most of these studies give vehicle travel in some base year and project travel into future years. Also, many of these are on-going studies capable of supplying up-to-date information.

If vehicle miles of travel projections are not available for a region, a projection can be made by using the vehicle miles of travel for any of the base years 1960, 1965, and 1968, and by assuming that the regional vehicle travel growth rate is the same as the expected average national growth rate. To do this, take the factor from Table 8-2 under the "base year" for the year of interest and multiply the miles of travel in the base year by this factor. This gives an estimate of vehicle miles of travel in the year of interest. This method is not as accurate as using actual projections of travel for a region, but does serve to give a rough estimate of future travel.

Table 8-2. FACTORS FOR ESTIMATING VEHICLE MILES OF TRAVEL[3]

Year of interest	Base year		
	1960	1965	1968
1960	1.00	0.82	0.75
1965	1.23	1.00	0.91
1968	1.34	1.10	1.00
1970	1.43	1.17	1.06
1975	1.69	1.38	1.26
1980	2.00	1.63	1.49
1985	2.37	1.93	1.77
1990	2.82	2.30	2.11

If neither future travel estimates nor base-year travel figures are available for emission estimates, base-year vehicle miles can be approximated by taking the total number of vehicle registrations and multiplying by the factor 9,400 (miles per year per vehicle registration).

These base-year travel estimates, when used with Table 8-2 and equations (1), (2), and (3), allow regional emission estimates to be made from vehicle registration data. This method is less accurate than either of the two vehicle travel methods, but it does provide rough estimates when travel information is not available.

No rule of thumb is available for determining what fraction of regional miles of travel is urban. One should try to distribute the travel into a bi-modal distribution, that is, urban travel at a 25-mph-average route speed and rural travel at a 45-mph-average route speed. The local transportation planning staff or the local traffic engineer may have valuable input for determining the best urban-rural distribution. It should be emphasized that this is a critical step in estimating regional emissions because of the significant differences in the urban and rural emission factors.

Table 8-3. EMISSION FACTORS FOR AIRCRAFT BELOW 3,500 FEET[4]
(lb/flight)[a]

Type of emission	Jet aircraft, four engine[b,c]		Turboprop aircraft		Piston-engine aircraft	
	Conventional	Fan-jet	Two engine	Four engine	Two engine	Four engine
Carbon monoxide	35	20.6	2.0	9.0	268.0	652.0
Hydrocarbons (as C)	10	29.0	0.3	1.2	50.0	120.0
Oxides of nitrogen (as NO_2)	23	9.2	1.1	5.0	12.6	30.8

[a] A flight is defined as a combination of a takeoff and a landing.

[b] No water injection on takeoff.

[c] For three-engine aircraft, multiply these data by 0.75; and for two-engine aircraft, multiply these data by 0.5.

Table 8-4. EMISSION FACTORS FOR DIESEL ENGINES[4]
(lb/1,000 gal diesel fuel)

Type of emission	Emission factor
Carbon monoxide	60
Hydrocarbons (as C)	136
Oxides of nitrogen (as NO_2)	222

8.2 EMISSION FACTORS

Tables 8-3 and 8-4 present emission factors for aircraft and diesel engine emissions.

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9. VEHICLE EMISSIONS RESEARCH AND DEVELOPMENT

9.1 GOVERNMENTAL

Under the Clean Air Act, as amended, the Secretary of Health, Education, and Welfare was assigned the responsibility for special emphasis on research and development into new and improved methods having industry-wide application for the prevention and control of air pollution resulting from the combustion of fuels. In accordance with that assignment, research has been undertaken under the direction of the National Air Pollution Control Administration (NAPCA) to develop solutions to problems of air contamination from mobile sources. Areas of research include low-emission power plants, improved-emission control methods for current types of engines, fuel modification, and indirect approaches such as mass transportation. Federal organizations active in relevant programs[1] are indicated in Appendix A. Additional programs sponsored by the National Air Pollution Control Administration[1] are listed in Appendix B.

As the pioneering organization in the control of vehicular emissions (as the former CMVPCB), the California Air Resources Board is continuing in research efforts to this end.

9.2 INDUSTRIAL

United States industrial companies and industrial associations, such as the American Petroleum Institute (API) and the Automobile Manufacturer's Association (AMA), are doing research and development work to alleviate the vehicle emissions problem individually and jointly as members of cooperating groups.[2,3] Among the latter are the Coordinating Research Council and the Inter-Industry Emission Control Program.

The Coordinating Research Council was established to coordinate research within the automotive and petroleum industries, which includes vehicle emissions research under the guidance of the Air Pollution Research Advisory Committee (APRAC). Council membership includes representation from the Federal Government and the automotive and petroleum industries. Appendix C of this document lists some projects sponsored by APRAC to reduce emissions from mobile sources.[1]

Qualified research organizations conduct designated projects under contract with the Council, which assigns project monitors from among its membership. Several projects under way, especially significant to this document, embrace the subjects of surveillance, inspection, and maintenance procedures for minimizing automotive emissions. Information from them will not be available until 1971 or 1972, however. Identified according to the specified objective,[4] they are:

CAPE*-14 – Develop a short-duration emissions inspection and maintenance procedure for state-owned and franchised inspection facilities.

CAPE-15, Task I – Develop a short-duration (approximately 3 min.) and a comprehensive (approximately 30 min.) engine/device parameter inspection and maintenance procedure.

CAPE-15, Task II and CAPE-16 – Execute a fleet testing program to evaluate emission and engine/device inspection and corresponding maintenance procedures.

CAPE-17 – Develop a short-duration emission inspection procedure to be used for surveillance purposes and plan an optimum surveillance program.

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*CAPE – Cooperative Air Pollution Engineering.

CAPE-18 – Prepare an economic effectiveness model and use it in the selection of inspection, maintenance, and surveillance procedures as well as to plan an "optimum" surveillance program.

Another teaming of industrial efforts is the Inter-Industry Emission Control program, conceived and established by the Ford Motor Company and Mobil Oil Corporation. This team, composed of U.S. and foreign auto manufacturers and U.S. oil companies, is now conducting a number of extensive programs to develop more effective methods of controlling automobile emissions. The program goal is to find a way to achieve even lower levels of automobile exhaust emissions than those called for by the 1970 standards. Fifteen projects toward this end are scheduled for completion by the spring of 1970. Chrysler and Esso Corporations are also cooperating in research to reduce vehicular emissions.

Most research and development relating to vehicle emissions is being conducted by private industry. Because of the proprietary nature of this research, however, no data are available on specific research funds or plans. Furthermore, the nature of the research itself is often kept secret until there are results to be announced. Some of the specific types of programs believed to be under way are discussed, however.[1]

9.2.1 Automobiles and Other Four-Stroke-Cycle, Spark-Ignited Engines

In anticipation of future regulations, the automobile, petroleum, and related industries are conducting considerable research both collectively and individually on the following control devices:

1. Afterburners, both catalytic and thermal.
2. Manifold reactors.
3. Exhaust recirculation.
4. Engine modification.
5. Fuel modification.
6. Evaporative control devices.
7. Filling and spillage control devices.

These areas probably make up the greatest part of all nongovernmental research aimed at reducing vehicle emissions.

9.2.2 Motorcycles and Other Two-Stroke-Cycle, Spark-Ignited Engines

Manufacturers of two-stroke-cycle engines are considering redesign of the engine to reduce emissions, or the use of an alternative engine, such as the Wankel engine. Very little research has been done to date, however.

9.2.3 Diesel Engines

Diesel manufacturers have been engaged in research on the reduction of nitrogen oxides, hydrocarbons, odor, and smoke through engine modifications and fuel additives.

9.2.4 Aircraft

Turbine engine manufacturers have conducted research into reducing visible smoke in the next generation of jet and turboprop engines. Little or no work has been done on piston engines.

9.2.5 Heat Engines

Automotive experience with Rankine cycle (steam) engines of recent design is very limited. Although the automobile manufacturers have not shown much interest, several industrial firms are pursuing Rankine research as a result of recent Congressional interest.

The Brayton cycle, or turbine engine, seems to be the unconventional engine of greatest interest to automobile manufacturers. It is considered the most desirable both for emission control and engineering feasibility. Manufacturers are conducting considerable research on this engine. One manufacturer has been testing several generations of prototype turbine automobiles for years. Other manufacturers, both in the United States and abroad, are directing their developments toward large commercial vehicle applications.

One Detroit manufacturer has invested a considerable amount of resources in developing Stirling cycle engines.

9.2.6 Electric Power Systems

Lithium-chlorine and sodium-sulfur battery systems are being developed by two automobile manufacturers. A petroleum manufacturer is far along in developing a capacitive high-temperature battery.

One of the most prominent programs on zinc-air batteries is being conducted by a consortium of British and American industrial firms. Various other industrial and chemical firms are developing zinc-air, sodium-air, and lithium-air batteries.

9.2.7 Hybrid Systems

Two joint ventures by an automobile manufacturer and a battery manufacturer are under way to produce a fuel cell-battery hybrid in one case, and a battery-battery hybrid in another. The latter approach is also being taken by an electric equipment manufacturer.

9.2.8 Photochemical and Atmospheric Research

Organic solvent manufacturers as well as the automobile and petroleum industries are sponsoring research concerning atmospheric photochemical reactions.

9.3 REFERENCES FOR SECTION 9

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2. Callahan, J.M. GM Details 19 Power Plants. Automotive News. May 26, 1969. p. 20-21.

3. Progress for Power Show–Steam, Electric Powered Cars Unveiled at General Motors. Technical Center (XP-883). General Motors Corp. Detroit News. May 7, 1969. p. 1A, 14A.

4. APRAC Status Report. Air Pollution Research Advisory Committee of the Coordinating Research Council, Inc. 30 Rockefeller Plaza, New York. April 1969. p. 25-29.

APPENDIX A

Federal Agencies Involved in Programs to Reduce Emissions from Mobile Sources

Agency	Program Area and Dates
National Air Pollution Control Administration	Controlling agency for all air pollution programs funded by U.S. Department of Health, Education, and Welfare (See Appendix B)
Atomic Energy Commission	Organic Rankine-Cycle Technology Investigation (1969-72)
	Status of High Energy Battery Developments (1969-70)
	Bimetallic Systems Program (electric power) (1969-75)
Department of Defense	Stratified Charge Engine (1969-70)
	Smoke Reduction in Turbine Aircraft Engines (1969-70)
	Industrial Gas Turbine Family (1969-75)
	AGT-1, 500 Gas Turbine Development (1969)
	Electrochemical Energy Storage for Vehicle Propulsion (1969-73)
	Exploratory Fuel Control Research (1969)
	Basic Combustion Research on Internal Combustion (1969-75)
Department of the Interior	Interactions Between Fuel Composition and Engine Factors Influencing Exhaust Emissions (1969-75)
	Products of Combustion of Distillate Fuels Used in Mobile Systems (1969-75)
	Evaluation of Fuel Composition Effects on Continuous Flow Combustion Propulsion Systems (1969-75)
	Characteristics of Photochemical Reactivity of Vehicle Emissions (1969-75)

Department of Transportation	Measurement of Smoke from Gas Turbine Engines (1969)
	Computer Programs to Define the Influence of Combustion Parameters in Turbine Engines (1970)
	Study of Visible Exhaust Smoke from Aircraft Jet Engines (1969)
	Rankine-Cycle Freon-Engine Bus System (1969-70)
	Rankine-Cycle Steam-Engine Bus System (1969-70)
	Stirling-Cycle Bus Systems (1970-71)
	Hybrid/Electric Bus System (1970-71)
General Services Administration	Providing Fleets of Vehicles for Use in Demonstration and Mileage Accumulation Tests.
	Fleet Test of Natural-Gas-Powered Vehicles (1970)
National Aeronautics and Space Administration	Development of Thermal Reactors for Vehicle Pollution Control (1969-71)
	Studies on Boilers, Pumps, Radiators, and Condensers (1969-72)
	Metal-Air Batteries (1971-75)
	Interagency Advanced Power Group (1969, 1971) (Includes AEC, DOD, HEW, and NASA)
Post Office Department	Fleet Test of Natural-Gas-Powered Vehicles (1970)

APPENDIX B

Programs Sponsored by NAPCA To Reduce Emissions from Mobile Sources

High Efficiency Induction Systems Evaluation (1969-71)

Carburetors, Reduction of Engine Exhaust Emissions (1969-70)

Influence of Fuel Atomization, Vaporization, and Mixing on Exhaust Emissions (1969-70)

Kinetics of Nitric Oxide at High Temperatures (1969-70)

Alternate Low Emission Fuels for Motor Vehicle Propulsion (1969-70)

Effects of Gasoline Additives on Carburetor and PCV System Performance as They Relate to Exhaust Emissions (APRAC - CAPE-2) (1969-70)

Emission Control Technique Evaluation (1969-70)

Evaluation of Exhaust Gas Recirculation for NO_x Control (1969-71)

Demonstrate Feasibility of Control of NO_x Emissions (1969)

Control of Nitrogen Oxides Emissions from Mobile Sources (1969-70)

Control of Particulate Emissions from Mobile Sources (1969-70)

Evaluation of Effects of Fuel Composition and Fuel Additives on Particulates in Exhaust Emissions (1969-70)

Fuel Volatility Effects on Driveability and Emissions (APRAC - CAPE-4) (1969-70)

Automotive Fueling Emissions (APRAC - CAPE-9) (1969-70)

Study of Two-Stroke-Cycle Spark-Ignition Engine Emissions (1969-70)

Development of Emission Factors for Off-Highway Internal Combustion Engine (1970)

Control of Emissions from Diesel-Powered Mobile Sources (1970)

Control of Particulate Emissions from Mobile Sources (diesel) (1970)

Fuel Injection System Analysis: Diesel Smoke Reduction (1969-70)

Investigation of Diesel-Powered Vehicle Odor and Smoke (1969-70)

Diesel Fuel Combustion Chemistry as Related to Odor (1969)

Control of Emissions from Aircraft (1969-70)

Rankine-Cycle Propulsion Systems for Vehicles (1969-70)

Low Emission Continuous Flow Combustors for Vehicle Propulsion Systems (1969-70)

Rankine-Cycle Bus Emission Evaluation (1970)

Gas Turbine Exhaust Emission Analysis (1969-70)

Irradiation Chamber Studies (1969-70)

Photochemistry and Kinetic Investigations (1969-70)

Elementary Reactions in Photochemical Smog (1969-70)

Field Studies of Photochemical Air Pollution (1969-70)

Atmospheric Reaction Studies in Los Angeles Atmosphere (APRAC - CAPE-7) (1969-70)

New Techniques for Exhaust Emissions (sampling) (1969-70)

Analytical Methods for Aromatics and Particulates in Auto Exhaust (APRAC - CAPE-12) (1970)

Improved Instrumentation for Determination of Exhaust Gases for NO_x and Oxygenate Content (APRAC - CAPE-11) (1969-70)

Chamber Reactivity Studies (APRAC - CAPA-1) (1970)

Response of Urban Population Groups to Diesel Exhaust Odors (1970)

Diesel Exhaust Odor Characterization (APRAC - CAPE-7) (1969-70)

Sampling System Evaluation (1969-70)

CO Profile Study (1970)

Diffusion Model of Urban Atmosphere (APRAC - CAPA-3) (1969-70)

Study of Air Pollution Aspects of Various Urban Forms (1970)

Development of Initial Guideline Document (1970)

Air Pollution Aspects of Various Roadway Configurations (Lower Manhattan Expressway) (1969-70)

Development of a Long-Range Program Plan for the Air Pollution Aspects of Environmental Planning (1969-70)

Engine Emission Reduction by Combustion Control (1969)

Kinetics of Nitrogen Oxides Automotive Pollution (1969-70)

UCB-ENG-2045—Combustion Gas Composition (1969-70)

Kinetics of Oxidation and Quenching of Combustibles in Exhaust Systems of Gasoline Engines (APRAC - CAPE-8) (1969-70)

Relation of Fuel Composition to Gaseous Exhaust Emissions from Automotive Vehicles (1969-70)

UCV-ENG-2365—Aromatic By-Products of Combustion (1969-70)

Liquid Fuel Ignition and Combustion (1969-70)

Gasoline Composition and Vehicle Exhaust Polynuclear Aromatic Content (APRAC - CAPE-6) (1969-70)

Combustion Process Analysis (1969)

Oxygenates in Automotive Emissions (1969-70)

Use of Electric Fields in Combustion (1969-70)

Long-Range R/D Program Plan for the Development of Motor Vehicle Control Technology (1969)

Long-Range Program Plan for Combustion Research (1969)

Long-Range R/D Program Plan for Air Pollution Instrumentation (1969)

Cost Effectiveness of Hydrocarbon Control (1969)

Technical Seminars, Advisory Committees, Etc. (1969)

APPENDIX C

APRAC Sponsored Projects Related to Emissions from Mobile Sources

ENGINEERING PROJECTS	Effects of Gasoline Additives on Carburetor and PCV System Performance As They Relate to Exhaust Emissions
	Fuel Effects on Combustion Chamber Deposits and Emissions
	Fuel System Time-Temperature Histories of Driver Habits
	Fuel Volatility Effects on Driveability and Emissions
	Gasoline Composition and Vehicle Exhaust Polynuclear Aromatic Content
	Diesel Exhaust Odor Characterization
	Kinetics of Oxidation and Quenching of Combustibles in Exhaust Systems of Gasoline Engines
	Automotive Fueling Emissions
	Improved Instrumentation for Determination of Exhaust Gas NO_2 and Oxygenate Content
	Analytical Methods for Aromatics and Particulates in Auto Exhaust
ATMOSPHERIC PROJECTS	Irradiation Chamber Studies
	Dispersion of Pollutants in an Urban Area

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